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Nanoparticle-Based Formulations of Antiparasitic Drugs: Advantages, Limitations, and Future Perspectives

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Abstract. Parasitic infections remain a major global challenge in veterinary medicine, affecting both animal welfare and agricultural productivity. These infections often result in chronic diseases and substantial economic losses, particularly in livestock. Although chemical antiparasitic drugs are the cornerstone of treatment and prevention, their clinical effectiveness is frequently limited by poor solubility, low bioavailability, rapid metabolism, and the growing problem of drug resistance. Such limitations have driven research toward innovative delivery strategies that can improve pharmacological efficacy. Nanotechnology has recently emerged as one of the most promising approaches in this regard. Nanoparticle-based formulations, including polymeric nanoparticles, liposomes, solid lipid nanoparticles, and metallic nanostructures, can enhance drug solubility, stability, and controlled release while enabling targeted delivery to intracellular parasites. Numerous studies have demonstrated the superior efficacy and reduced toxicity of nanoformulated antiparasitic drugs such as albendazole, ivermectin, praziquantel, artemisinin, and nitazoxanide. Furthermore, these nanosystems offer new opportunities for resistance management and the development of long-acting formulations that improve treatment compliance. This review summarizes current advances in nanoparticle-based antiparasitic therapies, emphasizing their pharmacological advantages and potential applications in modern veterinary pharmacology.

Keywords: Nanoparticles, antiparasitic drugs, nanotechnology, veterinary pharmacology

Antiparaziter İlaçların Nanopartikül Bazlı Formülasyonları: Avantajları, Sınırlamaları ve Gelecek Perspektifleri

Özet. Paraziter enfeksiyonlar, veteriner hekimlikte hem hayvan refahını hem de tarımsal üretkenliği olumsuz etkileyen önemli bir küresel sorun olmaya devam etmektedir. Bu enfeksiyonlar, özellikle çiftlik hayvanlarında kronik hastalıklara ve ciddi ekonomik kayıplara yol açmaktadır. Kimyasal antiparaziter ilaçlar, tedavi ve korunmanın temelini oluştursa da düşük çözünürlük, yetersiz biyoyararlanım, hızlı metabolizma ve giderek artan ilaç direnci gibi nedenlerle klinik etkinlikleri sıklıkla sınırlı kalmaktadır. Bu kısıtlılıklar, farmakolojik etkinliği artırabilecek yenilikçi ilaç taşıma stratejilerine olan ilgiyi artırmıştır. Son yıllarda nanoteknoloji bu açıdan en umut verici yaklaşımlardan biri olarak öne çıkmıştır. Polimerik nanopartiküller, lipozomlar, katı lipid nanopartiküller ve metalik nanoyapılar gibi nanopartikül temelli formülasyonlar; ilaç çözünürlüğünü, stabilitesini ve kontrollü salımını artırırken, aynı zamanda intrasellüler parazitlere hedefli ilaç iletimine olanak sağlamaktadır. Çok sayıda çalışmada, albendazol, ivermektin, prazikuantel, artemisinin ve nitazoksanid gibi antiparaziter ilaçların nanoformülasyonlarının, geleneksel formlara kıyasla daha yüksek etkinlik ve daha düşük toksisite sunduğu gösterilmiştir. Ayrıca bu nanosistemler, direnç yönetimi için yeni olanaklar sunmakta ve tedaviye uyumu artıran uzun etkili formülasyonların geliştirilmesine katkıda bulunmaktadır. Bu derlemede, nanopartikül temelli antiparaziter tedavilere ilişkin güncel gelişmeler özetlenmekte; bu yaklaşımların farmakolojik avantajları ve modern veteriner farmakolojisindeki potansiyel uygulamaları vurgulanmaktadır.

Anahtar Kelimeler: Nanopartiküller, antiparaziter ilaçlar, nanoteknoloji, veteriner farmakoloji

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1. Introduction

Parasitic diseases represent one of the major health and economic challenges in both human and veterinary medicine. Unlike bacterial infections, which typically have acute onset and distinct symptoms, most parasitic infections develop chronically and are often difficult to diagnose in the early stages, leading to significant economic losses in livestock production (Sun et al., 2019). After invading their host—either humans or animals—parasites can cause a wide range of pathological conditions. Transmission generally occurs through direct contact, the fecal–oral route, or via vectors. Due to the limited number of effective therapeutic options and insufficient pharmaceutical research, parasitic infections remain highly prevalent worldwide, affecting billions of individuals and causing approximately 14 million deaths annually (AlGabbani, 2023; Król et al., 2023). In veterinary medicine, chemical antiparasitic drugs continue to serve as the cornerstone for the control and treatment of parasitic diseases. These compounds play a critical role in maintaining animal health and ensuring productivity in livestock industries. However, many of these drugs suffer from poor solubility, short half-life, and limited bioavailability. Furthermore, because many parasites exhibit complex and lengthy life cycles, prolonged and repeated drug administration is often required to achieve therapeutic efficacy. This not only increases labor costs and animal stress but also contributes to the emergence of drug-resistant parasite strains (Sun et al., 2019).

Recent advances in nanotechnology have introduced new perspectives for combating parasitic infections. When materials are reduced to the nanoscale, their physicochemical properties, such as surface charge, stability, and reactivity, undergo significant alterations. Nanoparticles have been widely utilized in the diagnosis, monitoring, and treatment of infectious diseases, including bacterial, viral, fungal, and parasitic infections. These nanostructures exhibit unique mechanical, optical, and chemical characteristics, which can be tailored to improve drug solubility, enhance bioavailability, and facilitate targeted intracellular delivery. Promising outcomes have been reported in the application of various nanocarriers for the treatment of parasitic diseases (Bajwa et al., 2022). The present review aims to summarize recent progress in nanoparticle-assisted antiparasitic therapies, focusing on nanocarrier systems and their pharmacological advantages in improving drug delivery, overcoming resistance, and enhancing therapeutic outcomes in modern veterinary pharmacology.

2. Limitations of Current Antiparasitic Therapies

Antiparasitic drugs remain the primary option for controlling parasitic diseases in animals. In veterinary practice, conventional antiparasitic formulations are generally available as tablets, powders, or injectable solutions. However, most of these conventional forms exhibit poor absorption due to their limited solubility and are therefore excreted unmetabolized. For example, most benzimidazoles are poorly absorbed from the gastrointestinal tract because of their low solubility and chemical instability. Other antiparasitic agents, such as ivermectin and praziquantel, are susceptible to enzymatic degradation or inactivation in animals, resulting in a strong first-pass effect. In addition, their limited penetration through biological membranes and tissues leads to reduced bioavailability and insufficient therapeutic efficacy (Babita et al., 2018; Lu et al., 2017).

Many parasites, such as Leishmania spp., are intracellular pathogens, and their localization within host cells further reduces drug efficacy due to the weak transmembrane and intracellular transfer ability of most antiparasitic agents (Silva et al., 2016). Drug resistance has also become increasingly widespread among all major parasite groups (Prichard et al., 1980). This issue is particularly critical in ruminants and equines, where resistance to anthelmintic drugs has been widely documented, although the severity varies across geographic regions (Selzer and Epe, 2021). Large-scale use, incorrect dosing, and failure to rotate between different drug classes have led to the selection of resistant parasite populations, rendering previously effective anthelmintics less potent or completely ineffective (De Clercq et al., 1997; Kwa et al., 1994).

Such resistance has been reported for benzimidazoles, including albendazole and mebendazole. Studies on Haemonchus contortus—a gastrointestinal nematode of major veterinary importance—have shown that resistance to benzimidazoles is associated with single nucleotide polymorphisms in the β-tubulin isotype 1 gene at codons 167, 198, or 200 (Furtado et al., 2014; Jaeger and Carvalho-Costa, 2017). Compared to the rapid emergence of antibiotic resistance in bacteria, anthelmintic resistance in nematodes has developed more slowly under field conditions, typically taking four to ten years for each chemical class (Sangster et al., 2018). However, due to the limited number of chemically distinct anthelmintic groups available, resistance has

become increasingly prevalent. Most commonly used anthelmintics belong to one of four major chemical classes, benzimidazoles, imidazothiazoles, tetrahydropyrimidines, and macrocyclic lactones, and all compounds within a given class share similar mechanisms of action (Vercruysse et al., 2018). Consequently, resistance to one compound often confers cross-resistance to other members of the same class, a phenomenon known as the "class effect" (Prichard and Geary, 2019).

While resistance remains a major driver of innovation in antiparasitic drug development, there is also an urgent need for formulations with improved usability and compliance. Products offering prolonged efficacy or easier administration, such as long-acting livestock formulations or palatable oral chewables for companion animals, can enhance adherence to parasite control regimens (Selzer and Epe, 2021). In all these cases, there is a pressing demand for novel compounds with new modes of action, as well as alternative delivery systems capable of overcoming current therapeutic limitations (Selzer and Epe, 2021).

3. Nanoparticle-Based Drug Delivery Systems in Antiparasitic Therapy

Nanoparticles designed at the nanometer scale can be engineered to target and penetrate parasite-infected cells, thereby enhancing drug delivery efficiency and improving therapeutic efficacy (Schwarz, 1999; Zhu et al., 2014). In addition to their therapeutic applications, nanoparticles have been investigated for their potential in diagnosis, vector control, theranostics, bioimaging, and resistance management. They enhance drug performance by improving solubility, bioavailability, and sustained release profiles. Moreover, they can be functionalized with specific ligands to detect biomarkers that enable early diagnosis. Nanoparticles have also been explored for their ability to combine therapeutic and diagnostic functions in vector control and for their use in imaging and monitoring techniques (Tiwari et al., 2023).

With the rapid development of nanomedicine and the growing demand for effective treatments against parasitic diseases, nanoparticles, particularly organic nanocarriers, have attracted considerable interest for antiparasitic drug delivery. Organic nanocarriers are typically fabricated from natural or synthetic polymers, solid lipids at room temperature, phospholipids, or cholesterol. These materials are formulated into particles ranging from 10 to 1000 nm in diameter, providing a large specific surface area and strong adhesive properties, which result in exceptional drug-loading and targeting characteristics (Wagner et al., 2006). Various nanocarriers, including solid lipid nanoparticles (SLNs), polymeric nanosystems (such as nanospheres, nanoparticles, and micelles), nanocrystals, and liposomes, have been extensively investigated for the delivery of antiparasitic drugs.

Antiparasitic agents can be loaded onto nanoparticles through physical or chemical adsorption, encapsulation, or conjugation processes, and are subsequently released via desorption, dissolution, or degradation mechanisms. Depending on the therapeutic requirements and drug properties, these nanoparticles can be administered through multiple routes, including oral, dermal, pulmonary, or parenteral delivery (Chen et al., 2015; Hamori et al., 2014; Xu et al., 2017; Zhang et al., 2012). Such nanocarriers are capable of overcoming biological barriers, protecting drugs from enzymatic degradation, and providing desirable attributes such as targeted delivery, physical stability, controlled release, and effective intracellular transport and accumulation (Das and Chaudhury, 2011; Negi et al., 2013).

Immobilization of antiparasitic drugs onto or within nanoparticles has proven to be an effective approach to enhance therapeutic efficacy while minimizing toxic side effects (Sun et al., 2019). Although the application of nanotechnology in parasitic disease therapy is still in its early stages, it demonstrates significant potential for future development. Further studies are required to fully understand its mechanisms and to establish it as a widespread clinical tool (Tiwari et al., 2023). Overall, nanoparticles represent a promising strategy for both treatment and diagnosis of parasitic infections. Systems such as liposomes, polymeric nanoparticles, solid lipid nanoparticles (SLNs), nanosuspensions, and metallic nanostructures, including carbon, gold, and silver nanoparticles, are being widely investigated as advanced drug delivery systems for antiparasitic therapy (Tiwari et al., 2023).

4. Representative Examples of Nanoformulated Antiparasitic Drugs

Several experimental and preclinical studies have investigated nanoformulated antiparasitic drugs to enhance solubility, bioavailability, and therapeutic performance while minimizing toxicity. The following examples summarize recent advances across different nanoparticle systems and parasitic diseases. An overview of these formulations is presented in Table 1.

Table 1. Representative nanoformulated antiparasitic drugs and their key characteristics.

Drug	Nanocarrier Type	Target Parasite	Model	Key Outcomes	Reference
Albendazole	AgNPs	*E. granulosus*	Mice	↑ efficacy (63.9%); ↓ cyst size; ↓ hepatic damage	Nassef et al., 2019
Albendazole + Praziquantel	Chitosan NPs	*E. granulosus*	Mice	↓ cyst count & size; higher efficacy than drug suspensions	Torabi et al., 2018
Albendazole	Albumin-SLNs	*E. granulosus*	Mice	↓ cyst count, improved efficacy	Faizi et al., 2024
Fenbendazole	Nanocrystals	*T. crassiceps*	Mice	↑ dissolution; ↑ efficacy	da Silva et al., 2024
Ivermectin	NLC	*E. granulosus*	*In vitro*	100% protoscolex mortality	Ahmadpour et al., 2019
Ivermectin	Chitosan–alginate NPs	*Brugia malayi*	Rodent (*M. coucha*)	↑ Microfilaricidal activity at ½ dose; ↑ bioavailability; prolonged MRT	Ali et al., 2013
Ivermectin	SLN	*T. spiralis*	Mice	↓ worm burden, ↓ COX-2, improved liver/kidney function	Hammad et al., 2025
Praziquantel	SLNs	*S. mansoni*	*In vitro*	↑ efficacy; ↓cytotoxicity;	de Souza et al., 2014
Praziquantel	HCO-SLNs	*S. mansoni*	Mice	↑ bioavailability (14.9–16.1×); ↑ MRT; sustained release	Xie et al., 2010
Praziquantel	SNEDDS	*S. mansoni*	Rats	>95% parasite reduction; safe for pediatrics	Mengarda et al., 2025
Metronidazole	Lactoferrin NP	*T. gallinae*	Pigeons	↑ efficacy; faster clearance	Tabari et al., 2021
Metronidazole	Chitosan NPs	*G. lamblia*	Hamsters	↓ cyst/trophozoite counts; mucosal healing	El-Gendy et al., 2021
Metronidazole	AgNPs	*B. hominis*	*In vitro*	↓ viability (~80%); synergistic effect	Younis et al., 2020
Nitazoxanide	AgNPs	*Cryptosporidium*	Mice	↓ oocyst shedding; ↓ cytochrome C & caspase-3	Hassan et al., 2022
Artemether	NLCs	*L. major*	*In vitro*	↓ IC_{50}; high selectivity; low cytotoxicity	Rahnama et al., 2021
Artemisinin + Curcumin	Liposomes	*P. berghei*	Mice	Prolonged plasma levels; high efficacy	Isacchi et al., 2012
Amphotericin B	MTC	*Leishmania donovani*	*In vitro*	↑ uptake; ↓ IC_{50}; prolonged intracellular retention	Shahnaz et al., 2017
Rifampicin + Pentamidine	NLC	*Leishmania major*	BALB/c mice	↓ lesion size (4.8-fold); ↓ parasite burden	Almutairy et al., 2025
AgNPs	—	*Gigantocotyle explanatum*	*In vitro*	↓ motility; ↑ ROS; tegumental damage	Rehman et al., 2019
ZnO NPs	—	*P. equorum*	Rats	↓ larvae, improved renal biomarkers	Ali et al., 2024
AgNPs	—	*Toxoplasma gondii*	*In vitro* / Mice	↓ parasite proliferation; ↑ survival	Hematizadeh et al., 2023

Abbreviations*:* AgNPs – silver nanoparticles; ZnO NPs – zinc oxide nanoparticles; SLN – solid lipid nanoparticles; HCO-SLN – hydrogenated castor oil solid lipid nanoparticles; NLC – nanostructured lipid carriers; SNEDDS – self-nanoemulsifying drug delivery system; MTC – mannose-anchored thiolated chitosan; NP – nanoparticle; MRT – mean residence time; ROS – reactive oxygen species; IC_{50} – half-maximal inhibitory concentration; ↑ – increased/improved; ↓ – decreased/reduced.

a. Benzimidazole-based systems (Albendazole and Fenbendazole)

Nassef et al. (2019) evaluated the therapeutic potential of albendazole (ABZ) loaded onto silver nanoparticles (AgNPs) against *Echinococcus granulosus* infection in mice. Following 8 weeks of treatment, the ABZ–AgNP formulation achieved the highest efficacy rate (63.9%) among all groups, with marked ultrastructural damage to cyst walls and significant reductions in cyst size and weight. The study also reported normalization of serum IFN-γ and liver enzyme levels, indicating reduced hepatic inflammation compared with free ABZ. Histopathological examination revealed that AgNPs mitigated ABZ-induced necrosis and steatosis, suggesting a hepatoprotective effect of the nanocarrier system. According to the authors, the nanosilver-based delivery system improved the therapeutic performance of albendazole in experimental hydatidosis. Similarly, Torabi et al. (2018) investigated chitosan-based nanoparticles containing albendazole and praziquantel (ChABZ + ChPZQ) as a dual nanoformulation for the treatment of *Echinococcus granulosus*. The formulation was assessed both in vitro and in vivo, where the combined ChABZ + ChPZQ nanoparticles exhibited significantly greater reductions in cyst number and size than the corresponding free-drug suspensions. Transmission electron microscopy revealed marked degeneration and disorganization of the cyst wall, confirming enhanced scolicidal efficacy of the nanoparticulate combination compared with conventional suspensions. More recently, Faizi et al. (2024) developed cationized albumin-conjugated solid lipid nanoparticles (B-SLN + ABZ) as advanced carriers for albendazole delivery against *E. granulosus* infection. The nanoformulation, prepared by emulsification and solvent evaporation, demonstrated significantly greater prophylactic and therapeutic efficacy than both free ABZ and unconjugated SLNs. Mice treated with B-SLN + ABZ exhibited marked reductions in cyst number and wet weight, alongside pronounced ultrastructural damage in metacestodes, confirming the enhanced antiparasitic potential of albumin-linked solid lipid nanoparticles. da Silva et al. (2024) prepared a nanoformulation of fenbendazole using the antisolvent method with poloxamer 407 as a stabilizer and assessed its efficacy against *Taenia crassiceps* cysticerci in a murine neurocysticercosis model. The lyophilized nanocrystals (~400 nm) exhibited a markedly higher dissolution rate than the raw drug. *In vivo*, treatment with the nanoformulated fenbendazole led to pronounced alterations in the parasite's energy metabolism, particularly in mitochondrial pathways, and produced stronger antiparasitic effects compared with pure fenbendazole. According to the authors, these findings support the potential of nanoformulated fenbendazole as an effective therapeutic approach for neurocysticercosis (da Silva et al., 2024).

b. Ivermectin-based systems

Ahmadpour et al. (2019) assessed the cestocidal efficacy of ivermectin (IVM) encapsulated in nanostructured lipid carriers (NLCs) against *Echinococcus granulosus* protoscoleces. The NLC-loaded IVM achieved complete (100%) mortality at lower concentrations and shorter exposure times compared to free IVM, indicating enhanced potency. Moreover, upregulation of caspase-3 mRNA expression suggested that the nanoformulation induced stronger apoptotic activity within the parasite. Ali et al. (2013) also developed chitosan–alginate nanoparticles encapsulating ivermectin (IVM) to enhance antifilarial efficacy against *Brugia malayi*. In Mastomys coucha models, a single subcutaneous dose of nanoencapsulated IVM (200 μg/kg) exhibited significantly higher microfilaricidal activity than a double dose of free IVM (400 μg/kg). Pharmacokinetic analysis in rats showed increased peak plasma concentration, greater AUC, and prolonged mean residence time. Furthermore, co-administration with diethylcarbamazine amplified both micro- and macrofilaricidal effects, underscoring the superior therapeutic profile of the nanoformulation over conventional treatment. In another study, Hammad et al. (2025) evaluated ivermectin-loaded solid lipid nanoparticles (IVM-SLNs) in the treatment of the enteric phase of *Trichinella spiralis* infection. Mice receiving IVM-SLNs, especially in combination with albendazole, showed a significant reduction in adult worm burden, inflammatory infiltration, and apoptosis compared with untreated controls. The formulation also decreased COX-2 expression and improved hepatic and renal function indices, indicating enhanced therapeutic efficacy and safety over conventional ivermectin therapy.

c. Praziquantel-based systems

de Souza et al. (2014) developed solid lipid nanoparticles (SLNs) loaded with praziquantel (PZQ) to enhance solubility and therapeutic performance against *Schistosoma mansoni*. The nanoformulation showed stronger dose-dependent antiparasitic activity in *S. mansoni* cultures, leading to faster parasite death compared with free PZQ. The encapsulation of PZQ into SLNs also reduced cytotoxicity in HepG2 cells and provided a controlled release pattern, suggesting potential advantages for oral schistosomiasis therapy. In another study, Xie et al. (2010) formulated praziquantel-loaded hydrogenated castor oil solid lipid

nanoparticles (HCO-SLNs) and demonstrated a marked improvement in pharmacokinetic performance. The nanoformulation increased bioavailability by 14.9-, 16.1-, and 2.6-fold and extended the mean residence time of praziquantel up to 95.9, 151.6, and 48.2 hours following oral, subcutaneous, and intramuscular administration, respectively, compared with the conventional formulation (Xie et al., 2010). Recently, Mengarda et al. (2025) reported the development of a self-nanoemulsified praziquantel delivery system (SNEDDS-PZQ) designed for pediatric schistosomiasis. The formulation demonstrated a favorable safety profile and was suitable for semi-industrial pilot-scale production. *In vivo* studies showed over 95% parasite load reduction after a single oral dose of 200 or 400 mg/kg SNEDDS-PZQ, markedly surpassing the efficacy of free praziquantel. Pharmacokinetic analysis confirmed enhanced systemic exposure, highlighting the potential of this cost-effective nanoformulation for large-scale clinical use.

d. Artemisinin and derivatives

Artemisinin-based nanoparticle formulations have shown promising therapeutic potential for malaria and leishmaniasis. Compared with free artemisinin, nanoencapsulation enhances drug solubility, bioavailability, and antiparasitic efficacy while reducing systemic toxicity. Alven and Aderibigbe (2020) reviewed multiple nanoparticle systems, including polymeric, liposomal, and metallic carriers, and highlighted their ability to improve pharmacokinetic properties and overall therapeutic outcomes in both *in vitro* and *in vivo* studies (Alven and Aderibigbe, 2020). Isacchi et al. (2012) investigated liposomal formulations of artemisinin and artemisinin–curcumin combinations in *Plasmodium berghei*-infected mice. *In vivo*, both nanoencapsulated artemisinin (A-CL and A-PL) and artemisinin–curcumin (AC-CL and AC-PL) formulations produced rapid and complete parasite clearance, curing all infected mice within the same post-inoculation period, whereas free artemisinin showed delayed and fluctuating efficacy. The PEGylated formulation (A-PL) provided the most sustained plasma concentration and consistent antimalarial activity, suggesting that liposomal encapsulation enables controlled release and prolonged systemic exposure (Isacchi et al., 2012). In a related study, Rahnama et al. (2021) developed artemether-loaded nanostructured lipid carriers (ART-NLCs), which demonstrated significantly enhanced anti-leishmanial activity, lower cytotoxicity, and a higher selectivity index than free artemether, highlighting their potential as a safer and more effective option for *Leishmania major* infections (Rahnama et al., 2021).

e. Metronidazole and nitazoxanide nanoformulations

El-Gendy et al. (2021) evaluated the therapeutic efficacy of metronidazole-loaded chitosan nanoparticles (MTZ-CsNPs) against *Giardia lamblia* infection in hamsters. The nanoformulation achieved the highest reduction rates in cyst (94.7%) and trophozoite (94.3%) counts compared with either free metronidazole or chitosan nanoparticles alone. Histopathological analysis revealed marked mucosal healing and restoration of normal intestinal architecture following MTZ-CsNP treatment. According to the authors, encapsulating metronidazole in chitosan nanoparticles significantly enhanced its antiparasitic efficacy and tissue recovery compared with conventional therapy (El-Gendy et al., 2021). Younis et al. (2020) compared the in vitro efficacy of silver nanoparticles (AgNPs), metronidazole (MTZ), and their combination (AgNPs + MTZ) against *Blastocystis hominis*. Parasite viability decreased progressively over time, with the combined formulation achieving the greatest inhibition—approximately 80% reduction after 3 hours, surpassing either agent alone. The authors proposed that silver nanoparticles and MTZ-loaded AgNPs represent efficient alternative therapeutic candidates for *B. hominis* infection, although further in vivo and toxicity studies are still required to confirm their safety and mechanism of action (Younis et al., 2020). Hassan et al. (2022) assessed the therapeutic and apoptotic effects of silver nanoparticle–loaded nitazoxanide (AgNP–NTZ) in immunocompetent and immunosuppressed mice experimentally infected with *Cryptosporidium*. Treatment with AgNP–NTZ, at both full and half doses, achieved the greatest reduction in oocyst shedding and the most notable improvement in intestinal histopathology, surpassing the efficacy of either NTZ or AgNPs alone. Furthermore, AgNP–NTZ treatment markedly decreased cytochrome C and caspase-3 expression levels, indicating a modulatory effect on apoptosis. According to the authors, AgNP-NTZ represents a promising therapeutic candidate for *Cryptosporidium* infection in both immune conditions (Hassan et al., 2022). In another study, Tabari et al. (2021) investigated a metronidazole-loaded lactoferrin nanoparticle formulation (nano-MTZ) against *Trichomonas gallinae* in pigeons. The nanoformulation demonstrated greater therapeutic efficacy than conventional metronidazole, leading to faster eradication of trophozoites in infected birds. According to the authors, this lactoferrin-based delivery system may represent a promising carrier platform for developing improved metronidazole formulations in avian species, though further studies are required to clarify its pharmacokinetics, safety profile, and mechanism of action (Tabari et al., 2021).

f. Nanoformulations in Leishmaniasis

Shahnaz et al. (2017) designed long-acting mannose-anchored thiolated chitosan nanocarriers (MTC-AmB) for targeted delivery of amphotericin B against visceral leishmaniasis. The mannose-functionalized thiolated chitosan system improved macrophage uptake by approximately 71-fold compared with the free drug and maintained intracellular drug retention for up to 10 days. In vitro studies showed a markedly enhanced antileishmanial effect, with an IC_{50} value of 0.02 µg/mL for MTC-AmB compared to 0.26 µg/mL for native amphotericin B. According to the authors, this macrophage-targeted nanocarrier system provides a promising platform for improving the therapeutic efficacy of amphotericin B against intracellular *Leishmania* parasites (Shahnaz et al., 2017). In another study, Almutairy et al. (2025) developed a nanostructured lipid carrier (NLC) system co-loaded with rifampicin (RIF) and pentamidine (PTM) for the topical treatment of cutaneous leishmaniasis. In vitro assays demonstrated significantly enhanced antileishmanial activity, with IC_{50} values approximately 2.8-fold (promastigotes) and 2.6-fold (amastigotes) lower than those of free drugs, alongside reduced cytotoxicity to macrophages. *In vivo*, treatment with NLC-RIF/PTM gel in BALB/c mice resulted in a 4.8-fold reduction in lesion size and a marked decrease in parasite burden compared with conventional formulations. According to the authors, the dual-drug lipid nanocarrier addressed key challenges of existing therapies, such as drug resistance and poor topical delivery, highlighting the potential of co-loaded nanosystems as a future direction in leishmaniasis management (Almutairy et al., 2025).

g. Metal-based nanoparticles

Rehman et al. (2019) investigated the *in vitro* anthelmintic potential of biologically synthesized silver nanoparticles (AgNPs) against *Gigantocotyle explanatum*, a trematode parasite isolated from the bile ducts of Indian water buffaloes (*Bubalus bubalis*). Exposure to AgNPs led to severe tegumental damage, loss of motility, and reactive oxygen species (ROS)-mediated oxidative stress, as evidenced by increased lipid peroxidation, protein carbonylation, and DNA damage. These findings demonstrate that AgNPs can disrupt the antioxidant and detoxification systems of flukes, suggesting their potential as nano-based anthelmintic candidates for future *in vivo* evaluation (Rehman et al., 2019). Hematizadeh et al. (2023) further demonstrated the antiparasitic potential of plant-based AgNPs against *Toxoplasma gondii*. Silver nanoparticles synthesized using *Sambucus ebulus* and *Feijoa sellowiana* fruit extracts showed potent anti-toxoplasmic activity both in vitro and in vivo. Infected mice treated with Ag-NPs derived from *S. ebulus* exhibited a significant reduction in parasite proliferation and improved survival, comparable to the reference drug pyrimethamine. These results highlight the potential of biosynthesized metallic nanoparticles as effective and less toxic alternatives for antiparasitic therapy. Ali et al. (2024) explored the therapeutic potential of green-synthesized zinc oxide nanoparticles (ZnO NPs) against *Parascaris equorum* infection in male Wistar rats. Treatment with ZnO NPs (30 and 60 mg/kg) significantly reduced larval burden, improved renal biomarkers, and restored antioxidant levels compared to infected untreated animals. Histopathological and immunohistochemical analyses revealed marked protection of kidney tissues, indicating that biogenic ZnO NPs not only exhibit potent anthelmintic activity but also alleviate parasite-induced organ damage.

Collectively, these studies highlight the diversity and therapeutic promise of nanoparticle-based antiparasitic formulations. By improving pharmacokinetic behavior, enhancing cellular uptake, and reducing host toxicity, nanoformulations such as polymeric, lipidic, and metallic systems represent a major step toward next-generation antiparasitic chemotherapy in veterinary and medical applications.

5. Veterinary-Relevant Applications of Nanoformulated Antiparasitic Drugs

Nanotechnology has been applied across a wide range of veterinary species, with each host presenting unique parasitic challenges and therapeutic requirements. To understand the practical relevance of nanoformulated antiparasitic systems, it is essential to examine how these technologies have been implemented in real veterinary contexts. The following examples provide representative applications in various veterinary species, highlighting species-specific outcomes and the translational potential of different nanoformulation strategies. A comparative overview of these applications is presented in Table 2.

Table 2. Representative applications of nanoformulated antiparasitic drugs in veterinary species.

Species / Host	Target Parasite	Nanomaterial / Nanoformulation	Study Type	Key Outcomes	Reference
Cattle	*Rhipicephalus (Boophilus) microplus*, *Haemaphysalis bispinosa*	Green-synthesized TiO_2 nanoparticles (Cassia auriculata–mediated)	*In vitro*	100% larval mortality at 16 µg/mL; 90% nymph mortality; 74% and 68% adult mortality; inhibited egg hatch and arrested embryogenesis	Chandran et al., 2025
Goats	*H. contortus*	PLGA-encapsulated rHcARF1 nanovaccine	*In vivo*	Enhanced humoral and cellular immune responses; reduced egg shedding and worm burden	Hasan et al., 2024
Sheep	*Psoroptes* mange mites	Nano–zinc oxide as adjunct to doramectin	*In vivo*	Faster lesion healing and wool regrowth (day 15 vs. day 30); restored oxidative/biochemical parameters	Yousif et al., 2023
Dogs	*Ancylostoma caninum*	Albendazole nanocrystals	*In vivo*	Improved pharmacokinetics; complete egg shedding elimination at ¼ standard dose	Paredes et al., 2018
Cats / Dogs	*Ctenocephalides felis*	SiO_2-NPs	*In vitro*	96% flea mortality at highest concentration within 40 min; strong concentration–time dependent activity	Anah and Anah, 2023
Poultry (Broilers)	*Eimeria tenella*	Biosynthesized SeNPs	In vivo	↓ oocyst shedding; ↓ intracecal stages; improved antioxidant & immune markers; improved growth and carcass traits	Alsulami and El-Saadony, 2023
Domestic pigeons	*Ascaridia columbae*	Chitosan nanoparticles	*In vitro + in vivo*	Potent nematocidal effect; improved clinical signs; prevented mortality; restored oxidative and inflammatory markers	Salem et al., 2022
Fish (Carp)	*Argulus siamensis*	Green-synthesized AgNPs	*In vitro*	High mortality of copepodid and adult stages; possible ion-channel–related mechanism	Kumari et al., 2025
Rabbits	*Sarcoptes scabiei*	AgNPs and GNPs	*In vivo*	Rapid clinical improvement with anti-inflammatory molecular profile; no major toxicity (GNPs)	Hassanen et al., 2024

Abbreviations: AgNPs – Silver nanoparticles; GNPs – Gold nanoparticles; SeNPs – Selenium nanoparticles; SiO_2-NPs- Silica nanoparticles ; TiO_2 NPs – Titanium dioxide nanoparticles; PLGA – Poly(lactic-co-glycolic acid); rHcARF1 – Recombinant *Haemonchus contortus* ADP-ribosylation factor 1 antigen.

a. Ruminants

Rhipicephalus (Boophilus) microplus and *Haemaphysalis bispinosa* are major ticks causing substantial productivity losses in cattle, and resistance to conventional acaricides has become a critical challenge. A recent in vitro study evaluated green-synthesized titanium dioxide nanoparticles produced using *Cassia auriculata* flower extract. The nanoformulation showed potent acaricidal effects across multiple life stages of *R. (B.) microplus*, producing 100% larval mortality at only 16 µg/mL and up to 90% nymphal mortality. Adult mortality reached 74% for *R. (B.) microplus* and 68% for *H. bispinosa* at 100 µg/mL, markedly outperforming the crude plant extract and titanium precursor. The nanoparticles also inhibited egg hatchability and arrested embryonic development, indicating broad multi-stage efficacy. These findings highlight plant-mediated TiO_2 nanoparticles as a promising nanotechnological alternative to synthetic acaricides in livestock parasite management (Chandran et al., 2025).

Haemonchus contortus is one of the most pathogenic gastrointestinal nematodes in small ruminants, and increasing anthelmintic resistance has intensified interest in vaccine-based control strategies. Hasan et al. (2024) evaluated a PLGA nanoparticle–encapsulated recombinant ADP-ribosylation factor 1 antigen (rHcARF1-PLGA) as a nanovaccine candidate in goats. Immunized

animals exhibited significantly elevated serum IgG, IgA, and IgE levels and increased cytokine responses (including IL-4, IL-9, IL-17, and TGF-β) compared with non-immunized controls. Following experimental challenge with infective *H. contortus* larvae, the nanovaccinated goats demonstrated a 47.5% reduction in fecal egg counts and a 55.7% reduction in adult worm burden relative to the challenged unvaccinated group. Although protection was partial and the authors note the need for optimization of antigen dose and vaccination regimen, these results indicate that PLGA-based antigen delivery systems can enhance immune responses and provide measurable protective efficacy against *H. contortus* infection in goats.

Mange infestation is a major health and economic concern in sheep production, leading to severe skin lesions, wool loss, and reduced productivity. Yousif et al. (2023) investigated the therapeutic benefit of nano-zinc oxide supplementation as an adjunct to doramectin in sheep naturally affected by *Psoroptes* mange. Animals receiving nano-zinc supplementation showed markedly faster clinical improvement, with reduced pruritus, contraction of lesions, and visible wool regrowth by day 15, whereas animals treated with doramectin alone or with conventional mineral supplementation demonstrated comparable improvement only around day 30. Serum biochemical abnormalities associated with mange, such as decreased zinc levels, altered protein profile, and elevated enzyme activities, also normalized more rapidly in the nano-zinc group, reaching values similar to healthy controls by day 15. These results indicate that nano-zinc oxide supplementation enhances the rate of tissue repair and metabolic recovery during mange treatment and may serve as an effective supportive approach for improving outcomes in sheep.

b. Dogs and cats

Canine hookworm infections, particularly those caused by *Ancylostoma caninum*, remain a significant clinical concern in veterinary practice due to their pathogenic effects and increasing reports of anthelmintic resistance. The poor aqueous solubility and variable oral bioavailability of albendazole (ABZ) have long limited its therapeutic reliability in dogs, prompting the development of alternative delivery systems that can enhance drug performance. Paredes et al. (2018) evaluated a self-dispersible nanocrystal formulation of ABZ and demonstrated markedly improved pharmacokinetic behavior compared with a conventional product, reflected in increased systemic exposure to the active sulphoxide metabolite. In naturally infected dogs, the nanocrystal formulation achieved superior anthelmintic efficacy at reduced doses, with complete elimination of *A. caninum* egg shedding at one-quarter of the standard therapeutic dose. Importantly, the enhanced dissolution and pharmacokinetic performance of the nanocrystal formulation translated into full efficacy at significantly lower dosing, underscoring the potential of nanosizing strategies to reduce drug requirements without compromising clinical outcomes in dogs.

Ectoparasite infestations are a major challenge in companion animal medicine, particularly in cats and dogs, where *Ctenocephalides felis* is the most prevalent flea species and an important vector for zoonotic pathogens. Increasing resistance to conventional insecticides has driven interest in alternative control strategies, including nanoparticle-based formulations. Anah and Anah (2023) evaluated the *in vitro* fleacidal activity of silica nanoparticles (SiO_2-NPs) against adult *C. felis* collected from naturally infested domestic cats. The nanoformulation produced a clear concentration- and time-dependent killing effect, with the highest tested concentration achieving 96% mortality after 40 minutes, significantly outperforming negative controls. Although further in vivo studies are required, these findings indicate that SiO_2-NPs represent a promising and rapidly acting nano-enabled approach for flea control in companion animals and highlight the broader potential of nanotechnology in the management of ectoparasites resistant to conventional treatments.

c. Poultry and other avian species

Coccidiosis remains one of the most economically significant parasitic diseases in poultry, and the emergence of drug-resistant *Eimeria* strains underscores the need for alternative control strategies. Alsulami and El-Saadony (2023) investigated the efficacy of biosynthesized selenium nanoparticles (SeNPs) against experimental *Eimeria tenella* infection in broiler chickens. Dietary administration of SeNPs markedly reduced fecal oocyst shedding and significantly decreased the numbers of intracecal parasite developmental stages compared with untreated infected controls and birds treated with a conventional anticoccidial drug. Infection-induced oxidative stress was substantially ameliorated in SeNP-supplemented birds, accompanied by decreased expression of pro-inflammatory and apoptotic markers. Improvements were also observed in growth performance, carcass traits, antioxidant capacity, and hematological parameters. These findings demonstrate that SeNP supplementation provides strong anticoccidial, antioxidative, and immunomodulatory benefits in broilers experimentally infected with *E. tenella*.

Gastrointestinal parasitism represents a significant health challenge in domestic pigeons and other avian species, contributing to poor performance, increased susceptibility to secondary infections, and substantial economic losses. Identifying sustainable alternatives to conventional anthelmintics is therefore a priority in avian health management. Salem et al. (2022) reported that *Ascaridia columbae* was the most prevalent helminth in domestic pigeons and evaluated the therapeutic potential of chitosan nanoparticles against this parasite. The nanoformulation demonstrated potent *in vitro* and *in vivo* nematocidal activity, not only inducing destructive ultrastructural damage to the worms but also ameliorating clinical signs, preventing mortality, and promoting intestinal tissue repair in treated birds. In addition, infected pigeons showed marked elevations in oxidative stress and pro-inflammatory markers, which were significantly improved following chitosan nanoparticle treatment. These outcomes highlight the promise of biodegradable chitosan-based nanosystems as effective and host-beneficial antiparasitic agents for avian species, particularly in settings where resistance to conventional drugs is emerging.

d. Aquaculture species (Fish)

Nanotechnology-based approaches have also gained attention in aquaculture, where parasitic infestations such as argulosis pose a major threat to freshwater fish production. *Argulus siamensis*, a crustacean ectoparasite, is responsible for significant economic losses in carp farming, and the limited effectiveness and safety concerns of conventional chemotherapeutics have encouraged the search for alternative strategies. Kumari et al. (2025) reported that green-synthesized silver nanoparticles exhibited strong antiparasitic activity against both copepodid and adult stages of *A. siamensis*, achieving markedly higher mortality rates compared with traditional treatments. The study further indicated that nanoparticle exposure may influence ion channel–related signaling pathways, suggesting a potential mechanism underlying their antiparasitic effects. These findings highlight the promise of nanoformulations as safer and more sustainable tools for controlling parasitic diseases in aquaculture systems, complementing their emerging applications in terrestrial veterinary species.

e. Rabbits

Sarcoptes scabiei–induced mange is a common and economically significant ectoparasitic disease in rabbits, and emerging resistance to conventional acaricides such as ivermectin has intensified the search for alternative therapies. In a recent study, silver (AgNPs) and gold nanoparticles (GNPs) were evaluated as novel nano-acaricides in naturally infested pet rabbits. Both nanoparticle formulations produced marked clinical improvement, reducing lesion severity from a mean score of 3 at baseline to 0–1 after treatment, whereas untreated rabbits showed progression of lesions. Histopathological and molecular analyses demonstrated downregulation of pro-inflammatory markers (iNOS, TNF-α, COX-2, IL-6, IFN-γ) and upregulation of anti-inflammatory cytokines (IL-10, TGF-β), indicating enhanced tissue healing. Importantly, neither AgNPs nor GNPs induced adverse effects on liver or kidney biomarkers, although AgNP residues were detectable in hepatic tissue while GNPs showed no organ deposition. These findings suggest that particularly gold nanoparticles may represent a safe and effective alternative acaricide for managing sarcoptic mange in rabbits (Hassanen et al., 2024).

6. Advantages of Nanoparticle-Based Antiparasitic Formulations

Conventional antiparasitic chemotherapy often suffers from limited drug solubility, poor membrane permeability, and extensive enzymatic degradation, which lead to sub-therapeutic concentrations at infection sites. Nanoparticle-based formulations address these limitations by improving pharmacokinetic and pharmacodynamic performance. Encapsulation of antiparasitic agents within nanocarriers enhances solubility and bioavailability, shields the drug from premature degradation, and allows for controlled or sustained release, thus prolonging its therapeutic effect (Bashir et al., 2024; Alggabbani, 2023). The overall framework of nanoparticle-based antiparasitic drug delivery and their associated advantages are presented in Figure 1.

Nanocarrier systems also permit targeted and site-specific drug delivery, a crucial advantage for parasites that localize in particular organs or cell types. By manipulating particle size, surface charge, and ligand conjugation, nanoparticles can traverse biological barriers—such as intestinal epithelium or macrophage membranes—and accumulate selectively at infection sites (Li Pengyang et al., 2018). This targeted approach decreases systemic exposure and reduces toxicity to non-infected tissues while maximizing drug concentrations where parasites reside. Colloidal carriers like liposomes and polymeric nanoparticles have demonstrated improved efficacy and tolerability of existing antiparasitic drugs through such selective distribution (Date et al., 2007). Moreover, stimuli-responsive nanomaterials that release their payloads in response to pH or enzymatic changes—

characteristic of gastrointestinal or intracellular environments—enable precise drug release profiles that correspond to parasite niches (Bashir et al., 2024).

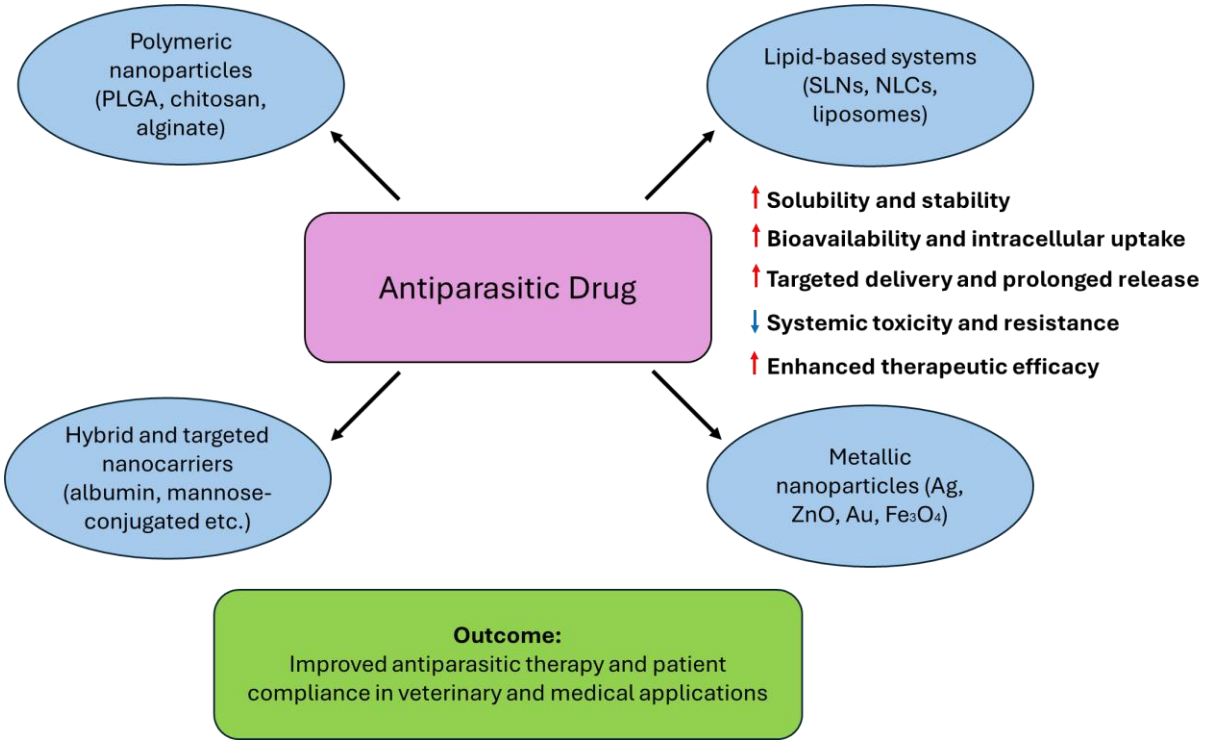

Figure 1. Schematic illustration of nanoparticle-based antiparasitic drugs.

Beyond pharmacological enhancement, nanoparticle-based formulations can contribute to resistance management and therapeutic safety. Controlled release and improved drug targeting reduce the need for high systemic doses, thereby lowering the selective pressure that promotes the emergence of resistant parasite strains. At the same time, nanocarriers mitigate off-target toxicities by limiting the interaction of potent antiparasitic molecules with healthy host tissues (Bajwa et al., 2022; AlGabbani, 2023). Although large-scale clinical adoption remains limited, the cumulative evidence demonstrates that nanotechnology provides a multifunctional platform capable of increasing treatment efficacy, decreasing adverse effects, and improving patient and animal compliance (Butt et al., 2025).

7. Limitations and Challenges of Nanoparticle-Based Antiparasitic Formulations

Although nanotechnology-based formulations have shown great promise in antiparasitic therapy, their large-scale clinical translation remains limited. Regulatory frameworks and manufacturing standards for veterinary and medical nanomedicines are still under development, and issues such as biodistribution, safety, and large-scale reproducibility continue to pose significant challenges (Butt et al., 2025).

A major difficulty lies in the production and stability of nanoparticle systems. Liposomal and lipid-based formulations are highly sensitive to temperature, radiation, and chemical sterilization, making large-scale preparation and long-term storage challenging. Achieving sterility often requires submicron filtration, while stability depends on additional steps such as freeze-drying and the use of cryoprotectants (Nas et al., 2018). Moreover, large-scale manufacturing involves costly raw materials and equipment, which limits commercial feasibility (Saleem et al., 2019).

Toxicological safety remains another concern. Although nanoparticles can reduce the adverse effects of conventional drugs, some nanomaterials, such as cationic liposomes and metallic nanoparticles, may cause cytotoxicity or oxidative stress at high concentrations. Silver nanoparticles, for example, have been linked to DNA damage and enzymatic inhibition in non-target organisms, highlighting the need for thorough biosafety assessments and the development of biocompatible, biodegradable materials (Latif et al., 2024; Krol et al., 2023).

From a regulatory perspective, nanoformulated antiparasitic drugs face barriers related to quality control, testing protocols, and approval procedures. Despite promising preclinical data, few have advanced to clinical use due to the absence of harmonized standards and limited stability under tropical conditions where parasitic diseases are prevalent (Mengarda et al., 2022).

Finally, economic constraints, including high production costs and limited infrastructure in developing regions, hinder widespread implementation. Conventional antiparasitic drugs such as amphotericin B remain more accessible and cost-effective, while most nanoparticle systems are still in experimental stages with unoptimized costs (Saleem et al., 2019).

In summary, the transition of nanoparticle-based antiparasitic formulations from laboratory to clinic is limited by toxicity, physicochemical instability, scalability, and regulatory uncertainty. Addressing these issues will be crucial for realizing the full therapeutic potential of nanotechnology in parasitic disease control.

8. Nanoparticle Toxicity, Environmental Safety, and Food Chain Considerations

Nanomaterials offer therapeutic and nutritional advantages in veterinary medicine, yet their use also raises important toxicological and environmental concerns. Metal-based nanoparticles such as zinc oxide or selenium nanoforms may induce oxidative stress, inflammatory responses, and genotoxic alterations depending on dose, particle size, and exposure duration, highlighting the importance of careful dose regulation and safety assessment (Rahman et al., 2022). Reports of reproductive disturbances, tissue accumulation, and species-specific variability further indicate that long-term safety data remain insufficient and that standardized guidelines for veterinary applications are still underdeveloped (Kazemi, 2025). These considerations are particularly relevant for food-producing animals, where potential residue persistence and environmental release require systematic evaluation and regulatory oversight. Oral exposure to nanoparticles, particularly those migrating from food, packaging, or environmental sources, has been linked to oxidative stress, protein denaturation, gastrointestinal injury, and DNA damage, emphasizing the need for rigorous exposure assessment and controlled use in livestock species entering the food chain (Biswas et al., 2022).

Beyond animal-level toxicity, the broader adoption of veterinary nanomaterials also raises concerns regarding environmental accumulation and ecosystem-level effects. Contemporary reviews highlight that increased use of nanoscale feed additives, drug carriers, and vaccines necessitates stronger regulatory infrastructures, as widespread application without adequate oversight may result in unintended ecological and biological consequences (Danchuk et al., 2023).

International regulatory bodies have emphasized that nanospecific risk assessment requires detailed physicochemical characterization, evaluation of dissolution and degradation behaviour, and adapted toxicological testing strategies—since nanomaterials may exhibit biological and toxicokinetic properties distinct from their bulk counterparts (EFSA Scientific Committee et al., 2021). Thus, future progress in veterinary nanotechnology will depend on balancing therapeutic innovation with clearly defined safety, environmental, and regulatory safeguards.

9. Conclusion and Future Perspectives

Nanotechnology has opened new horizons in the prevention and treatment of parasitic diseases by addressing some of the fundamental limitations of conventional antiparasitic drugs. Through improved solubility, bioavailability, and targeted delivery, nanoparticle-based systems have demonstrated enhanced therapeutic efficacy and reduced systemic toxicity. Various nanoscale carriers such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, and metallic nanostructures have shown promising results in controlled drug release and site-specific action, contributing to better treatment outcomes and improved compliance in both human and veterinary medicine.

Despite these promising advances, the transition of nanoparticle-based antiparasitic formulations from experimental research to clinical and commercial use remains challenging. Future efforts should focus on developing safer, biodegradable nanomaterials with reproducible large-scale synthesis and long-term stability under diverse environmental conditions. Comprehensive *in vivo* evaluations and standardized testing protocols will be essential to ensure biosafety and therapeutic reliability. Interdisciplinary collaboration among material scientists, pharmacologists, and regulatory authorities will also play a critical role in transforming nanotechnology from a promising concept into a practical and affordable tool for global parasite control.

Based on the available evidence in veterinary target species, several systems demonstrate short-term clinical transition potential. These include self-dispersible nanocrystals of benzimidazoles for canine helminth control, selenium nanoparticles as supportive anticoccidial agents in poultry, and nano-zinc oxide as an adjunct treatment for mange in small ruminants. These formulations rely on materials and manufacturing approaches already compatible with current regulatory frameworks, increasing their likelihood of practical adoption.

In the medium term, nanovaccine platforms, such as PLGA-encapsulated recombinant antigens against gastrointestinal nematodes, as well as plant-mediated metal oxide nanoparticles for tick management in cattle, may advance toward field application once optimization and safety validation are completed. These systems offer strategic advantages, including dose reduction, prolonged immune stimulation, and decreased reliance on conventional acaricides and anthelmintics, that align with current needs in veterinary parasitology.

Overall, the integration of nanotechnology into veterinary antiparasitic therapy is expected to progress in stages, beginning with nano-enabled enhancements of existing drugs and supportive supplements, followed by more complex immunomodulatory and vaccine-based platforms as evidence accumulates. Identifying formulations with the highest translational potential will help guide research priorities and accelerate the clinical adoption of nanoparticle-enabled antiparasitic strategies. In parallel, future development of nanoformulated antiparasitic drugs must be coupled with rigorous toxicological assessment, environmental risk evaluation, and food-chain safety monitoring to ensure that therapeutic innovation is aligned with long-term One Health principles.

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