



Potential Role of Biosynthesized Nanoparticles against Hard Ticks of Ruminants

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ABSTRACT

Hard ticks (Ixodidae family) are ectoparasites that present a serious health risk to ruminants through their mode of disease transmission for anaplasmosis, Lyme disease, and babesiosis. Acaricides have long been used to manage ticks but given the risk of acaricide resistance and environmental issues, new methods have been necessitated. Nanoparticles (NPs) are becoming more popular as antiparasitics, antibacterials, and antivirals since they possess distinctive characteristics of having a high surface area and rapid action. Thus, it is an improved method for tick treatment. Biosynthetic Zn, Cu, and AgO NPs are found to be highly toxic to ticks as they induce oxidative stress, disrupt vital metabolic processes, and damage cellular architecture. These NPs induce paralysis and death by touching tick cuticles and organs. On top of that, biosynthetic NPs would also enhance the effectiveness of existing acaricides by breaking through the resistant mechanism, thereby providing a dual control approach for tick control. As per recent studies, NPS have also been utilized in the formulations of acaricides, animal feed, or insect repellents to combat infestations of pests. However, it is important to critically analyze the potential health and environmental risks caused by the consumption of NPs throughout the cycle of agricultural production. In a bid to enhance their use in cattle health care, this study investigates the probable applications of NPs in tick management with a focus on effectiveness, challenges, and prospects for future studies.

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INTRODUCTION

The hard tick is one of the world's major bloodsucking arthropods (Ergunay et al. 2024). They transmit many viruses that can kill or cause substantial harm to domesticated animals, individuals, and wildlife (de la Fuente et al. 2023). Ixodidae is the family of hard ticks that rank second to mosquitoes as a carrier of disease, along with delivering direct harm to their host (Perumalsamy et al. 2024). Ticks belong to the phylum Arthropoda, class Arachnida, order Acari, and suborder Ixodida. The suborder Ixodida consists of two families: the family Ixodidae (the hard ticks) with marked sexual dimorphism, and the family Argasidae (the soft ticks) in which dimorphism is not distinct. The hard tick family Ixodidae currently comprises 786 species worldwide (Kahl and Gray 2023; Robbins et al. 2025). They are referred to as "hard ticks" due to their hard shield, or scutum, also because of

its hard chitinous shield which surrounds the adult male's entire dorsal surface and a small portion in the adult female, larva, and nymph (Johnson 2023).

The signs and symptoms include physical trauma and an immune response caused by salivary secretions generated by ticks, leading to cutaneous symptoms, causing discomfort, irritation, or hypersensitivity (Akhoundi et al. 2020). Severe infestations of ticks may lead to anemia due to blood loss (Akhtar et al. 2023). Prolonged attachment of hard ticks may result in erythematous macules, papules, nodules, and ulcers (Thomas and Reichard 2021). However, in animals, every time a tick bites to feed, it leads to stress and causes immunosuppression, which impacts their productivity and results in reduced production of milk and meat, higher morbidity, and, in several instances, causes mortality, along with indirect losses in the economy for producers associated with prevention and control costs (Yadav and Upadhyay 2024). Ticks consume blood

regularly, with lengthy periods between meals. Whenever they attack their hosts, it results in irritation, hypersensitivity, or inflammation of the tissues near the feeding site (Akhtar et al. 2023).

Hard tick attack can produce lesions that can give rise to secondary bacterial infections, localized dermatitis, and myiasis when flies feed on bleeding areas (Diaz 2023). The saliva of certain ticks contains paralyzing toxins that may kill the animals they attack. In African cattle species, saliva can also result in eczema (Schröder 2025). Around the world, adult females and males of the tick species attack domestic ruminants more often than their nymphal and larval stages (Nasirian 2024). At the attachment sites of domestic ruminants, the following tick species exhibited the most severe levels of parasitism: thigh, ear area, belly, dewlap and neck, udder or scrotum, tail, and anal region, and dorsal surface (Nasirian 2024).

Domestic ruminants, including buffaloes, goats, sheep, cattle, and camels, immensely serve the economies of human cultures through the generation of energy, food, crop manure, and raw materials worldwide (Mottet et al. 2018). The recent research highlights how hard ticks harm the economy of livestock farming. Due to ticks and tick-borne diseases, the people of India have faced economic losses of USD 787.63 million, from reduced milk production, costly treatments, and a reduction in the value of animal hides (Singh et al. 2022). Damage to livestock caused by *Rhipicephalus microplus* each year is estimated at somewhere between USD 22-30 billion globally (Pérez-Martínez et al. 2023). Tick infestations in Pakistan decrease productivity and cause major problems for milk and meat yields, resulting in increases in veterinary costs (Khan et al. 2022a).

Treatments to control hard ticks traditionally use chemicals from the organophosphate, pyrethroid, and amidine families, which are sprayed, used in dips, or as pour-ons (Phillips 2020). Many farmers apply them for their quick results in getting rid of ticks (Tamari et al. 2024). Continuous and frequent use of these chemical acaricides causes tick resistance. Other than resistance, these chemical acaricides cause environmental pollution (Margaoan et al. 2025). People in rural areas also depend on the use of traditional methods involving neem (*Azadirachta indica*), tobacco (*Nicotiana tabacum*), and garlic (*Allium sativum*) to control ticks (Mughal et al. 2023). Taking away hosting animals and rotating grazing grounds are other ancient strategies to keep ticks down (Riseth et al. 2020). Even though traditional techniques are affordable and long-lasting, they are usually not as effective as using different methods together. So, as a result, experts now suggest using both traditional methods and modern tick control techniques to protect against tick-borne diseases. Active immunization against ticks by vaccination against antigens essential to survive and/or transmit pathogens has been promising, but species-specific and vaccine efficacy is often constrained by immune variation (Wilson et al. 2020; Rocha et al. 2022). Nevertheless, the emergence of resistance, environmental issues, and poor cross-species vaccine efficacy are preventing long-term sustainability despite decades of effort to control it (Bhowmick and Han 2020). Table 1 gives different chemical drugs used to treat

hard ticks, including their mode of action, resistance mechanism, and possible limitations.

Due to tick resistance, cost-effectiveness, toxicity, and ecological imbalance, researchers are finding safe alternatives (Abbas et al. 2024). Nowadays, nanotechnology has emerged as a remarkable and advanced field. Nanoparticles (NPs) and nanomaterials of 1–100 nm range have brought revolution in science due to their physical, chemical, and biological properties (Tawade and Wasewar 2023). These NPs and nanomaterials are particularly well-suited for use in environmental science, medicine, and agriculture due to their quantum effects, increased surface-to-volume ratios, and changed reactivity (Rafeeq et al. 2025). NPs are composed of metals, polymers, ceramics, lipids, or a composite (Khan et al. 2022). Further, they are in the right size range for their ability to interact with biomolecules, cross biological barriers, and induce medicinally useful or diagnostic effects (Waheed et al. 2022). For example, polymeric NPs have been heavily applied in drug delivery due to their biocompatibility; biosynthetic NPs, gold nanoparticles (AuNPs), and silver nanoparticles (AgNPs) are antibacterial, antiparasitic, and anti-cancer (Croitoru et al. 2024; Abbas et al. 2025; Iqbal et al. 2025). NPs control parasites by entering their membranes, binding to proteins, and interfering with metabolism (Mahmoud et al. 2025). They produce reactive oxygen species (ROS), which break down parasites' proteins, lipids, and DNA (Pawłowska et al. 2023). AgNPs alter membrane permeability and enzymatic activity, while zinc oxide (ZnO) and titanium oxide (TiO₂) NPs are reported to be larvicidal and toxic to parasite cuticles (Gabrielyan et al. 2020; Fantatto et al. 2025). It has also been established that the incorporation of NPs carrying the drugs, such as chitosan, improves treatment efficiency and offers toxicity minimization (Herdiana et al. 2021). Generally speaking, nanotechnology presents a sustainable means of regulating parasites. The primary concern of this review article is the potential application of biosynthetic NPs to defend ruminants against hard tick attack.

Need for biosynthetic NPs

Also, due to their residual activity in meat, milk, and the environment, conventional acaricides are perceived as threats to the environment and food safety. One of the options is biosynthetic NPs (e.g., silver, zinc oxide, and titanium dioxide) (Fantatto et al. 2025). Biosynthesized NPs derived from microorganisms and plants have physicochemical properties, like their small size, high surface area, and increased reactivity. These properties enable them to enter the tick cuticle and disrupt physiological processes, making them so important in tick control (Fantatto et al. 2025). Compared to traditional acaricides, biosynthesized NPs induce metabolic interference, oxidative, DNA, and protein damage, and they reduce the likelihood of resistance expression in ticks (Fantatto et al. 2025). Their additional application holds great potential to substitute the application of chemical acaricides due to them being biodegradable, relatively affordable, and can be produced through the application of biological equipment (Muneer et al. 2023).

Table 1: Shows the traditional chemical drugs with mode of action and limitations.

Chemical Drug	Structural formula	Brand name	Mode of action	Resistance reported for the 1st time	limitations	References
Cypermethrin	C ₂₂ H ₁₉ C ₁ 2NO ₃	Cipermex®, Cyperkill® , Cyperguard®	Disrupting nerve function, prolonged opening of sodium channels leads to hyperexcitability and ultimately death.	1990	High resistance rate, environmental impact, and short residual impact	(Sindhu et al. 2022)
Metaflumizone	C ₂₄ H ₁₆ F ₆ N ₄ O ₂	ProMaris® , Alverde®	Blocks voltage-gated sodium channels, leading to tick paralysis and death	---	Resistance, limited availability	(Niklas et al. 2023)
Pyriprole	C ₁₈ H ₁₀ C ₁ 2F ₅ N ₅ S	Prac-tic®	Inhibits GABA-gated chloride channels, leading to paralysis	---	Limited approval, resistance	(Grosclaude 2023; Kolics et al. 2023).
Amitraz	C ₁₉ H ₂₃ N ₃	Tactic®, Mitac®, Tick-Off®	Inhibits octopamine receptors, affecting the nervous system, leading to paralysis and death	1980–1981	Resistance, toxicity, and environmental concerns	(Makuvadze et al. 2020; Tibebu and Assefa 2023)
Fipronil	C ₁₂ H ₄ C ₁₂ F ₆ N ₄ O ₅	Frontline® , Effitix®, Parastar®	Inhibits gamma-aminobutyric acid-gated chloride channels, disrupting neural transmission and causing paralysis	2007–2009	Resistance, safety concerns	(Torrents et al. 2020; Shakya et al. 2020)
Fluazuron	C ₂₀ H ₁₀ C ₁ 2F ₃ N ₃ O ₃	Various regional brands	Inhibits chitin synthesis, preventing molting in immature ticks and reducing egg hatching	2014	Persist in fat tissue, requires withholding periods before slaughter, may be excreted in milk	(Reshma and Prakasan 2020)
Spinosad	C ₄₁ H ₆₅ N ₁₀	Various regional brands	Disrupts acetylcholine binding at nicotine acetylcholine receptors, leading to tick paralysis and death	---	Efficacy may vary, and resistance development in the tick	(Reshma and Prakasan 2020)
Deltamethrin	C ₂₂ H ₁₉ B r ₂ NO ₃	Selmore®	Disrupts sodium channels in tick neurons	1979	Short residual activity, resistance development, and environmental persistence concerns	(Rahman et al. 2022)
Ivermectin	C ₄₈ H ₇₄ O ₁₄	Neguvon® , Ecofleece®	Macrocyclic lactone binds to glutamate-gated chloride channels, causing paralysis or tick death	2010	Resistance development, environmental impact, and withdrawal periods before slaughter	(Rahman et al. 2022)
Chlorfenvinphos	C ₁₂ H ₁₄ Cl ₃ O ₄ P	Various regional brands	Inhibits acetylcholinesterase receptors, leading to tick paralysis and death	2000–2001	Short residual activity, resistance development, and environmental persistence concerns	(Githaka et al. 2022. Evans et al. 2024)

Synthesis and characterization of biosynthetic nanoparticles

Most biosynthesized NPs are synthesized by green synthesis techniques involving natural biological agents to transform metal ions into NPs, i.e., bacteria, fungi, algae, and plant extracts (Salem and Fouda 2021), as shown in Fig. 1. Depending on the reducing and stabilizing properties of the phytochemicals or biomolecules contained in these biotic sources, this green method is eco-friendly (Bhatt and Saraswat 2024). To enhance the stability as well as efficacy of treatment, plant extracts are prepared and used as a model to reduce metal salts to NPs and also coat the

particles (Bao et al. 2021). Top-down and bottom-up synthesis are the two broad types; the latter is more common owing to the high level of control over particle shape and size (Escudero et al. 2021). Various techniques are utilized to investigate these NPs, including the use of UV-visible spectroscopy to identify optical characteristics, scanning electron microscopy (SEM) or transmission electron microscopy (TEM) to identify morphology and size analysis, X-ray diffraction (XRD) to identify crystallographic structure, and Fourier-transform infrared spectroscopy (FTIR) to identify the functional groups on the surface of NPs (Anukiruthika et al. 2020). Current

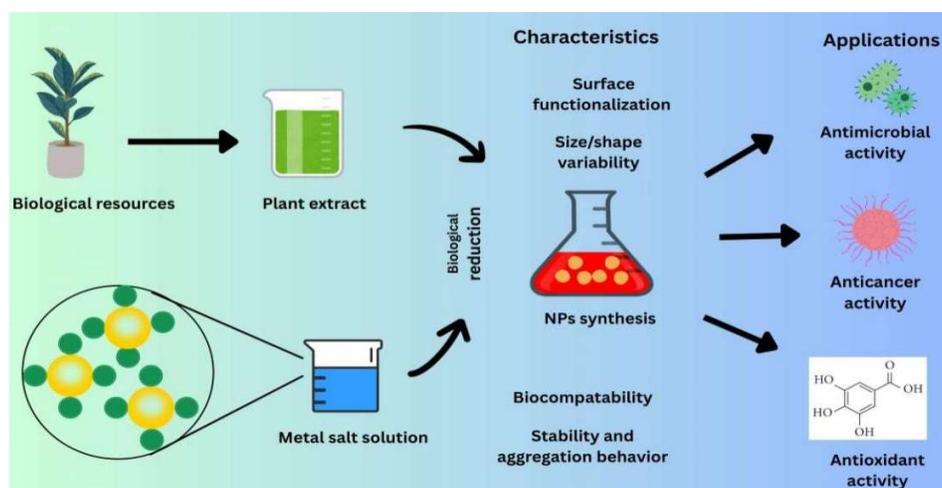


Fig. 1: Synthesis of nanoparticles from plant extract.

research advancement of NPs from silver, selenium, iron, and copper with definite physicochemical properties to utilize in agriculture and biomedicine (Khan et al. 2025). Biosynthesis using plants, in addition to being cost-saving and scalable, is less toxic environmentally than chemical synthesis (Kirubakaran et al. 2025). Increased research is being done on their possible acaricidal application against ruminant hard ticks as a result of the greater bioavailability, local deliverability, and minimal ecological footprint of these biosynthesized NPs (Fantatto et al. 2025).

Mode of Action of Biosynthetic Nanoparticles

Biosynthetic NPs are currently used as appealing options for carrying a variety of pharmacological biomolecules, both large and small, because of their distinctive electrical, catalytic, optical, and magnetic properties (Jamkhande et al. 2019). These properties are due to their mode of action as described below.

Oxidative Stress

NPs, including silver, zinc oxide, and copper oxide NPs, have an acaricidal effect on hard ticks due to the generation of oxidative stress. These NPs enter into the cuticle of the tick and produce reactive oxygen species (ROS) that cause the disruption of cellular components such as lipids, proteins (Zaheer et al. 2022a), and DNA, thereby damaging the mitochondria and causing cell apoptosis (Hernandez et al. 2022). Dysregulation between the ROS generation and antioxidant defense system in ticks leads to oxidative damage, which hinders important physiological processes and culminates in death (Mukherjee et al. 2024). Zinc oxide is one of the finest (ZnONPs), and it is used in the textile, agricultural, medical, healthcare, food, and engineering industries (Mohammed et al. 2019). Physical, chemical, and biological (bacterial, fungal, plant, algal, and viral) methods might be applied to produce ZnONPs. In one of the research studies, it was demonstrated that ZnONPs coated with cypermethrin were applied to *Rhipicephalus* ticks in each life stage of ticks, and they showed potential effects (Zaheer et al. 2023). In other studies, it was evaluated that ZnONPs, SeNPs, or CdSNPs induce cell damage, thereby emitting reactive oxygen species (ROS) (Patil 2020; Kadir et al. 2025). Similarly, graphene oxide

(GONPs), platinum (PtNPs), cobalt (CoNPs), or copper (CuNPs) also have ROS and oxidative stress on ticks (Senbill et al. 2025; Minwuyelet et al. 2025). Furthermore, a toxicity pathway can be started when zinc ions are released in interaction with the epidermis of living, non-mammalian organisms (Zaheer et al. 2021). The cypermethrin coated with zinc showed significant oxidative stress in arthropod tissues (Zaheer et al. 2023).

DNA and Protein Damage

AgNPs, ZnONPs, and CuONPs, or CoNPs, are NPs that have potent acaricidal effects on hard ticks via DNA and protein destruction. These NPs produce too many ROS within the tick cells, and this induces oxidative stress, which causes the destruction of cellular components. The nucleic acids are the target of the ROS attack, which leads to a breakage in DNA transcription, damage of DNA bases, and their fragmentation, disrupted replication and transcription processes involving tick survival (Dubey et al. 2020). NPs can attach to the amino acids S and P in nucleic acids and proteins, limiting the permeability of cell membranes and triggering organelle and heat degradation, which can contribute to cell death (Zaheer et al. 2022b). For example, ZnO and ZnS NPs coated with cypermethrin were applied on *Rhipicephalus* ticks, showing significant genotoxic and cytotoxic characteristics with a slight level of DNA damage (Zaheer et al. 2023). Similarly, AgNPs decrease the permeability of cell membranes by attaching to proteins and nucleic acids. The breakdown of enzymes causes cell death (Zaheer et al. 2022b). In another study, AgNPs produced from aqueous leaf extract of *Manilkara zapota* and *Cissus quadrangularis* showed the greatest tick death rate (Malak et al. 2025). Similarly, silver chloride (AgClNPs) affects protein interaction, and selenium (SeNPs) showed antioxidant modulations in ticks (Kadir et al. 2025). The trypsin enzyme and AgNPs produce strong bonds that block malarial absorption and impede tick development and reproduction (Benelli 2018). AuNPs may interfere with tick growth by suppressing the trypsin enzyme (Majeed et al. 2023). Titanium oxide (TiONPs) may influence the production of proteins and nucleic acids as they are smaller and thus readily cross the nuclear membrane (Li et al. 2023).

Physical damage to the exoskeleton

Physical damage to the tick exoskeleton can be achieved through the attachment and penetration of NPs, including Ag, CuO, and ZnONPs. These particles disturb the protective coating of wax and cause abrasions or cracks in the chitinous architecture, which results in higher water loss, desiccation, and loss of barrier effect (Arcot et al. 2024). Nanostructures can regulate arthropod growth and development due to their physicochemical characteristics, mainly their shape, size, and composition (Fantatto et al. 2025). Throughout the manufacturing process, formulation parameters need to be adapted for effective arthropod control (Kianfar and Sayadi 2022). As silicon (SiNPs) adhere to the cuticle layers of ticks, waxes, and lipids are consumed physically, leading to cell water loss and, ultimately, cell death (Naidu et al. 2023). The exoskeletons of ectoparasites are damaged by TiO₂NPs produced by plants, which limits their ability to move (Malak et al. 2025). In one of the research studies, it was evaluated that TiO₂NPs extracted from crown flower (*Calotropis gigantea*) showed a 100% tick death rate (Maddikontla et al. 2023).

Neurotoxic and metabolic disruption

Several ticks, including *Rhipicephalus* (*Boophilus*) *microplus*, are treated using numerous targets, which play neurotoxic and metabolic roles, causing low viability and death (Pottinger 2019). The neurotoxic disruption involves mainly the blocking of neurotransmission routes. NPs (in particular AgNPs and ZnONPs) affect the neuronal functionality by degrading synapses (Tripathy et al. 2025). CuONPs lower the level of ATP, induce swelling of mitochondria, and prevent detoxification enzymes (Cameron et al. 2022). The metals such as magnesium, zinc, and iron are reported to control cellular processes in arthropods. The MgONPs have been found to demonstrate potent lethality through cell membrane permeability, conduction, and excitability of nerves and intermediary metabolism. Likewise, zinc plays an important role in DNA synthesis, mitosis, cell proliferation, and the intracellular antioxidant action of arthropods (Zaheer et al. 2022b). It is still not known whether MgONPs produced insect lethality, although the anti-pathogenic effect has been attributed to DNA and (subsequent) cell wall damage, caused by the generation of ROS and owing to the consequent elevated alkalinity (Zaheer et al. 2022a). Exposure to AgNPs causes

blockage of major metabolic enzymes affecting glutathione S-transferase (GST), catalase (CAT), and superoxide dismutase (SOD) enzymes, impairing the methods of detoxification and cellular respiration (Martínez-Cisterna et al. 2024). The mechanism of action of NPs is shown in Fig. 2, and the acaricidal and repellent effect of some of the important NPS is shown in Table 2.

Limitations and Future Perspective

Nanotechnology holds much promise for veterinary parasitology, but its application against hard ticks is in its nascent stages and is fraught with disadvantages. There are few available field trials and no set procedure for the assessment of pharmacokinetics, safety, and efficacy of NPs in ruminants (Zhu et al. 2020). In addition, the long-term environmental impact still remains poorly understood, and commercialization is still encumbered by ambiguous regulatory barriers (Isibor 2024).

Despite all these challenges, the development of eco-friendly, target-specific nano-acaricides with persistent action and minimum toxicity must be the priority agenda for upcoming studies. While the development of nano-delivery systems like slow-release products or drug encapsulations will enhance dose efficiency, administration, and resistance management, green synthesis employing the use of plant extracts and natural stabilizers is a viable alternative. For translation of laboratory discoveries to safe and useful applications in the field, there must be interdisciplinary cooperation between veterinary medicine, parasitology, nanotechnology, and environmental sciences.

Conclusion

A breakthrough in veterinary parasitology is the application of biosynthetic NPs as an innovative approach for controlling ruminant tick infestations. Despite their various strategies for action, small size, and large surface area, these NPs, mainly silver, zinc oxides, and copper, have shown considerable acaricidal properties. Through generating the inhibition of essential enzymes, DNA damage, and oxidative stress, NPs may impact tick physiology at the molecular and cellular levels, as compared to traditional chemical acaricides. This multi-targeted technique of action may enhance the effectiveness of tick prevention strategies and minimize the probability of resistance development. The generation of NPs by bio-

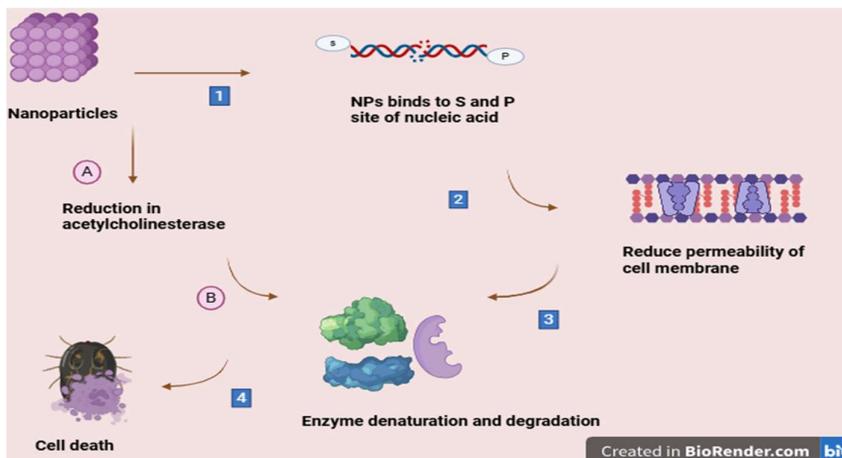


Fig. 2: shows that NPs (1) bind to nucleic acid S and P site (2), resulting in denaturing the DNA, disrupting the replication, (3) when binds to cell membrane, limiting the permeability of cell membranes and triggering organelle and heat degradation (4) loss or reduction of enzyme activity, the breakdown of enzymes causes cell death. On the other side, A shows that NPs also reduce the enzyme acetylcholinesterase, which also causes enzyme degradation (B), ultimately leading to tick death.

Table 2: Modes of action of Biosynthesized NPs against Hard Ti

Biosynthesized NPs	Source	Formation	Size	Mode of Action	References
NiO NPs	Chinaberry tree, Nickel nitrate hexahydrate	Biogenic and chemical synthesis	21-31 nm	Nucleic acids and proteins are affected by oxidative stress, and the exoskeleton impairs	(Abdel-Ghany et al. 2021)
Ag NPs	Silver plate	Chemical	10-100 nm	Disrupt tick physiology	(Zaheer et al. 2022b)
ZnO NPs	Neem, lemon grass	Biogenic	15-25 nm	Disruption of cellular mechanisms, decelerates key biological processes	(Zaheer et al. 2021)
TiO ₂ NPs	Titanium target	Chemical	81.04 nm	Osmotic pressure, oxidative stress induction, photocatalytic enzyme degradation	(Al Salih et al. 2023)
MgO NPs	Magnesium chloride hexahydrate	Chemical	-	DNA damage, cell wall disruption, generation of ROS species	(Zaheer et al. 2022b)
Fe ₂ O ₃ NPs	Iron chloride tetrahydrate	Chemical	-	Oxidative stress, cellular disruption	(Zaheer et al. 2022b)
AuNPs	Gold salt, plant extract	Citrate reduction.	10-50 nm	Oxidative stress, cell surface protein, drug delivery carrier	(Zaheer et al. 2022b)
SeNPs	Na ₂ SeO ₃ , garlic, fenugreek seed	Ascorbic acid reduction, phytochemical-mediated	50-200 nm	Antioxidant modulation, ROS imbalance, apoptosis induction, reduce fecundity and survival	(Kadir et al. 2025)
AgCINPs	Plant based	Plant based	-	Affects protein interaction, oxidative stress, and cell membrane disruption	(Zaheer et al. 2022b)
GONPs	Composite with copper chemical synthesis	Chemical	Nanoscale varied	Oxidative stress, interacts with biological membranes and modulates antioxidant defense enzyme modulation in ticks	(Senbill et al. 2025)
CuNPs	Copper sulphate, cupric chloride	Reduction with ascorbic acid, hydrazine	2-50 nm	ROS and oxidative stress, respiratory system disrupts, protein denaturation	(Senbill et al. 2025)
CoNPs	CoCl ₂ , neem, aloe vera	Chemical reduction, phytochemical-assisted	5-60 nm	ROS production, DNA damage, protein binding, enzyme inhibition, affect cuticle and egg viability	(Minwuyel et al. 2025)
PtNPs	Potassium hexachloroplatinate or platinum chloride	Reducing the platinum ion precursor by using a plant extract	1.3-35 nm	Oxidative stress is induced by reactive oxygen species (ROS) generation, disruption of cellular function, interference with enzyme activity, and damage to cell membranes.	(Minwuyel et al. 2025)
CdSNPs	cadmium salts like cadmium nitrate with hydroxide ions, using a plant extract	Chemical synthesis, plant-based synthesis	42 nm, 84 nm	Oxidative stress is induced by reactive oxygen species (ROS) generation, disruption of cellular function, interference with enzyme activity, and damage to cell membranes.	(Patil 2020)

based or green methods could be favorable for their effectiveness as well as their biodegradability and environmental concerns. However, problems still exist despite these positive results. Further research is needed to understand the tissue accumulation of NPs, the long-term effects on environmental safety and animal health, and the rules and regulations of the environment within their use in veterinary medicine. With all factors, parasitic control of ruminants might be improved through the integration of NPs in tick management strategies, increasing animal health and production, and decreasing dependence on conventional insecticides. Further research is required to ensure the safe, long-term, and efficient use of this modern technology in cow health management.

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