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The Antibacterial and Antiparasitic Activity of the Moringa-Derived Phytochemicals and Nanoparticles

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ABSTRACT

Bacterial and parasitic infections are the reasons for substantial public and livestock health and financial difficulties. Conventional chemical drugs such as antibiotics and anthelminthic agents have been utilized for decades, but due to antimicrobial resistance and severe toxic effects, their effectiveness is continuously compromised. Consequently, alternative medicinal strategies have been investigated, with plant-derived components attracting significant interest. Moringa has gained recognition as a potential organic source of biologically active substances with strong therapeutic potential. These bioactive substances cause disintegration of bacterial cell membranes, enhance oxidative stress, and block bacterial replication by disrupting the structural integrity of DNA, essential proteins, enzymes, and bacterial biofilms. Similarly, Moringa has also been responsible for the significant reduction of parasitic loads in tested animals. This review article aims to highlight the antibacterial and antiparasitic potential of Moringa-derived phytochemicals and nanoparticles, explaining their mode of action, efficacy, and applications. Moreover, it also discusses various future perspectives considering the novel, effective, eco-friendly, and large-scale application of Moringa and its NPs.

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INTRODUCTION

Bacterial and parasitic infections are the major threats for both humans and animals globally. Bacterial infections include mastitis, salmonellosis, tuberculosis (Khawbung et al. 2021), collibacillosis, etc. (Xuan et al. 2023), while parasitic infections resulting from trematodes, ticks, and nematodes are trypanosomiasis, leishmaniosis, Crimean Congo hemorrhagic fever, and schistosomiasis (Cummings et al. 2022). Moreover, these infections are the reasons for significant economic losses globally. Increased animal death rates, decreased yield, and costly medical procedures are the factors causing economic losses in the livestock sector (Strydom et al. 2023). In the same way, increasing dangers of animal-to-human diseases emphasize the importance of preventing infection in animals to lessen the dangers of potential pandemics and, consequently, substantial economic decline (Sharan et al. 2023).

For decades, chemotherapeutic drugs have been utilized to manage and control the effects of microbial and helminthic-induced infections (Wasan et al. 2022). Nevertheless, various limitations mitigate the efficacy and efficiency of these drugs. For example, the improper use and overuse of these medicines lead to the emergence of antibiotic resistance in both animals and humans, which is a global challenge associated with high mortality rates (Li et al. 2022; Sukmawinata et al. 2025). Furthermore, another limitation is the adverse effects triggered by these chemical drugs. For example, carbenicillin is an antibiotic that is used to treat serious bacterial infections but is also known for its toxic effects in patients, including eosinophilia, hepatotoxicity, leukopenia, and thrombocytopenia (Svitlana et al. 2021).

However, alternative medicinal techniques to combat microbial and helminthic infections have been gaining attention due to the disadvantages of conventional medical treatments. The recent advancements include probiotics, prebiotics, botanicals, and NPs (Abbas et al. 2025; Iqbal et al. 2025). However, plants and their derived products, including phytochemicals and NPs, have been studied to control and manage bacterial and parasitic infections. For example, Moringa, a miracle tree, is known for its medicinal and economic importance (Prajapati et al. 2022). The phytochemicals of Moringa and its NPs can be obtained by using different parts, including leaves, bark, sap, oil, roots, and flowers (Pareek et al. 2023). Moringa contains a broad spectrum of natural antioxidants, such as moringin (Saskia 2022; Wen et al. 2022), flavonoids (Hamed et al. 2024), terpenoids (Abdulmalik et al. 2024), alkaloids (El-Sherbiny et al. 2024), and tannins (Ayyanar et al. 2024) are known for their potential medicinal properties such as hepatoprotective (Saki et al. 2023), antioxidant (Srivastava et al. 2023), wound healing (Mohammad et al. 2022), anticancer (Rafique et al. 2023), antidiabetic (Hamza et al. 2023), antimicrobial (Royani et al. 2023), neuroprotective (Azlan et al. 2023), cardioprotective (Mohamad et al. 2025), anti-inflammatory (Chis et al. 2023), and anticoagulant (Nguyen and Nguyen 2024). Similarly, Moringa-derived metal NPs are considered more significant and demanding than lab-generated counterparts because of their eco-friendly and biodegradable nature. Various studies have demonstrated that different parts of the *M. oleifera* plant have been utilized heavily for the formulation of a variety of NPs, such as copper oxide (CuO), magnesium oxide (MgO), zinc oxide (ZnO), silver (Ag), gold (Au), nickel (Ni), nickel oxide (NiO), iron (Fe), selenium (Se), and calcium (Ca) (Bindhu et al. 2020; Shahbazi et al 2020; Mehwish et al. 2021). Moreover, clinical studies showed astonishing biological activities of green-synthesized NPs, including cytotoxic, anticancer, anti-inflammatory, antidiabetic, antioxidant, antiparasitic, antiviral, and antibacterial (Kiran et al. 2021; Younas et al. 2023; Ahmed et al. 2025; Ambrose et al. 2025). Also, due to their atomic-scale size, they exhibit significant medicinal properties through better penetration, bioavailability, focused targeting, and stability (Younas et al. 2023; Kaka et al. 2025). This review article explores the antibacterial and antiparasitic properties and mechanism of action of Moringa and its derived NPs.

Synthesis of Moringa NPs

Three main stages exist in the bioformulation of metal NPs from Moringa plant extract (Barman et al. 2023). The process begins with the initiation stage, which consists of reducing metallic ions and reduced metal atom nucleation to form initial NPs (Virk et al. 2023). It is followed by the growth stage, where heterogeneous nucleation leads to aggregation of newly synthesized large particles while enhancing their thermodynamic stability (Perumalsamy et al. 2024). Finally, in the termination stage, NPs attain their final morphology. Termination stage NPs are considered among the most energetically favorable configurations, mostly due to the ability of Moringa plant extract to stabilize metal NPs (Vidaarth et al. 2024). However, it is believed that Moringa extracts, which consist of various phytochemicals like flavonoids, saponins, terpenoids, saponins, and alkaloids and are derived from different parts of the plant, are the reason for the specific medicinal properties of these NPs (Bindhu et al. 2020; Irfan et al. 2021).

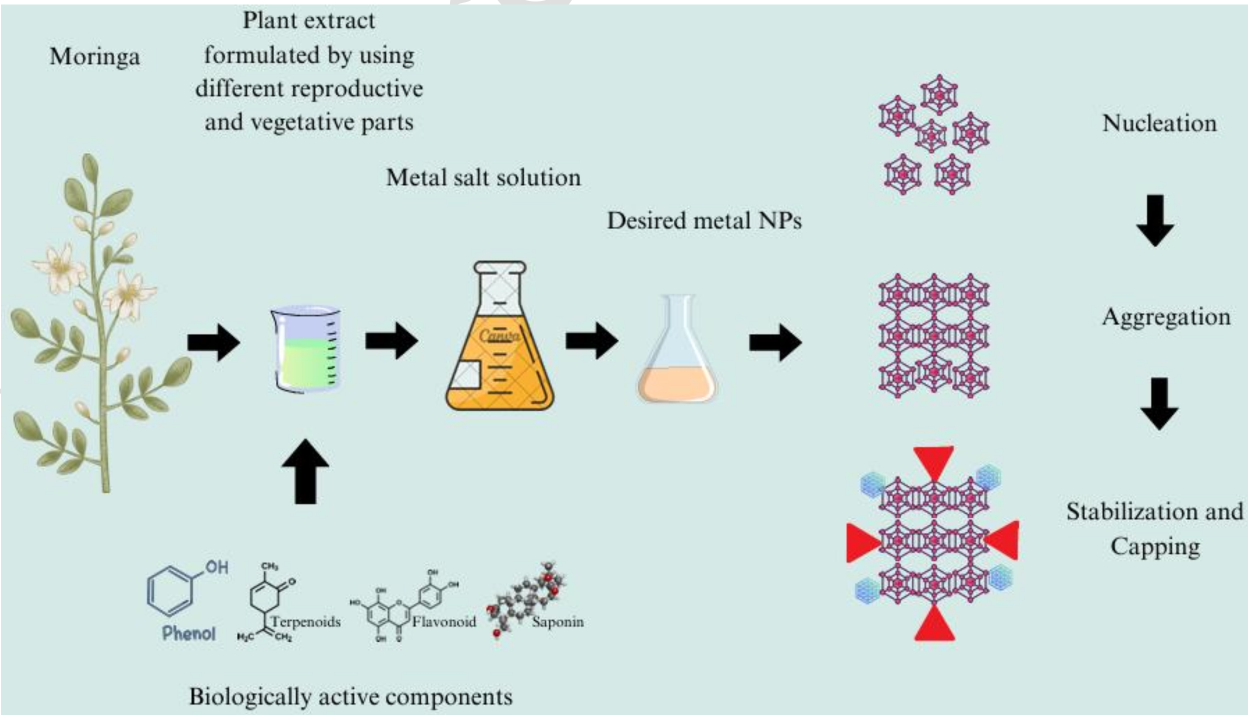

Fig. 3: Production of green synthesis of NPs from different reproductive and vegetative parts of the Moringa.

Antibacterial mechanism of action of Moringa and its NPs

The Moringa plant and its NPs have received considerable recognition due to their potential bacteriostatic and bactericidal properties, establishing it as an herbal alternative to synthetic antibiotics (Mahaveerchand and Abdul Salam 2024; Maskur et al. 2025). Various studies documented that Moringa can combat the resistance caused by antibiotics and propose economical medicinal options (Allam et al. 2024). Its wide range of biologically active natural antioxidants has been reported to show antibacterial properties through various modes of action. Damage to the bacterial cell wall and cell membrane (Zhao et al. 2022), inhibition of bacterial biofilm (Oliveira et al. 2023), and excessive production of oxygen radical species result in blockage of protein synthesis and denaturation of DNA, as shown in Figure 2. These processes ultimately inhibits bacterial replication and cause mortality (Afolabi et al. 2022; Wang et al. 2022). All these mechanisms are discussed below.

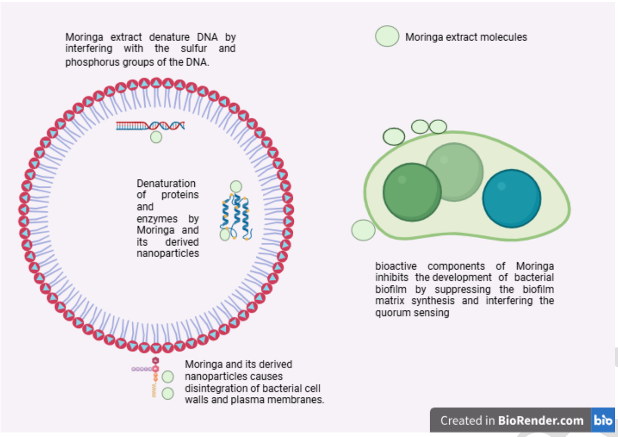

Fig. 2: Antibacterial mode of action of Moringa and its synthesized NPs.

Damaging the cell wall and cell membrane

The most common mechanism in the cascade of bacteriostatic activities of phytochemicals of Moringa and its NPs is usually damaging the cell wall and cell membrane, followed by the formation of nanopores. This results in an increase in membrane permeability, loss of intracellular components, and consequently, cell death (Riyadi et al. 2021). Coriolano et al. (2020) reported that the cell walls of *Serratia sp*. and *Streptococcus pneumoniae* were disrupted by a well-known bioactive compound known as lectin derived from Moringa. Lectin worked by binding to bacterial carbohydrate motifs and peptidoglycan constituents, causing membrane degradation. As a result, there is the efflux of intracellular components, stimulation of the apoptotic cascade in the bacterial cell, and eventually inhibition of bacterial growth. Gan et al. (2022) revealed the antibacterial therapeutic potential of moringin, an isothiocyanate isolated from the plant seed of Moringa. Moringin is responsible for the disintegration of the bacterial cell wall of gram-positive *Listeria monocytogenes* by destabilizing its peptidoglycan layers (Wen et al. 2022). In another study conducted by Branco et al. (2022), it was reported that Mo-CBP3-PepI, a synthetic peptide originating from the chitin-binding protein isolated from *M. oleifera*, showed excellent efficacy against *Klebsella pneumoniae* at a minimum concentration of 31.25 µg/ml. The positively charged Mo-CBP3-PepI binds to the negatively charged cell membrane of *K. pneumoniae*, resulting in the formation of large pores and surface damage and, ultimately, the induction of oxidative stress in the bacterial cell due to disruption in the antioxidant defense mechanism. Similarly, Irfan et al. (2021) reported that green-synthesized Ag and ZnO NPs by *M. oleifera* induce structural disintegration of cell membranes of *E. coli*, *Staphylococcus aureus, and methicillin-resistant S. aureus* by incorporating into the lipid bilayer, forming nanopores and leakage of ions and small molecules.

Production of reactive oxygen species

Moringa and Moringa-derived NPs can block the growth and proliferation of bacteria by inducing excessive oxidative stress in bacteria through elevated production of reactive oxygen species, including hydroxyl radicals (OH), hydrogen peroxide (H_2O_2), and Superoxide radicals (O_2^-) (Neto et al. 2017) and simultaneous suppressing of antioxidant enzymes activity such as catalase and superoxide dismutase (SOD) (Afolabi et al. 2022).

Fatiqin et al. (2021) revealed that MgO NPs derived from *M. oleifera* showed strong antibacterial activity against gram-positive bacteria *S. aureus* and *E. coli* by triggering excessive production of reactive oxygen species. Similarly, according to Ali et al. (2024), the immobilized AgNPs in the defensive gum of *Moringa oleifera* triggered oxidative stress in *B. subtilis, E. coli, K. pneumoniae, P. mirabilis, P. aeruginosa,* and *S. typhi,* with effective concentrations ranging from 25 µL to 200 µL. Moreover, Irfan et al. (2021) revealed that *M. oleifera*-based AgNPs and ZnO NPs induced oxidative stress in *E. coli* and *S. aureus* and disrupted bacterial cell structural integrity. Hence, these studies demonstrated that Moringa NPs induced oxidative stress in bacteria is one of the prime factors that suppresses the growth and replication of bacteria by damaging cellular proteins, enzymes, lipids, and nucleic acids.

Damaging DNA

Moringa and Moringa-derived NPs can directly attack the bacterial DNA and stop their replication. Mostly, they bind with the positively charged proteins of the bacterial DNA and cause its denaturation (Wang et al. 2023). In a study, Karthika et al. (2023) reported that *M. oleifera*-derived copper and nickel NPs inhibited the growth and proliferation of *Bacillus cereus* after interfering with the sulfur and phosphorus-containing DNA, resulting in destabilization of cellular proteins and DNA denaturation. Shalaby et al. (2022) reported that *M. oleifera*-synthesized AgNPs showed bactericidal properties. The study confirmed that AgNPs bind with the bacterial proteins, leading to the inhibition of protein synthesis and DNA replication in *B. subtilis, Enterococcus faecalis, S. aureus, E. coli, P. aeruginosa,* and *S. typhimurium.* Moreover, Mohammed et al. (2022) reported the antibacterial activity of Moringa-derived AgNPs through modification in the genomic sequence of *S. aureus, K. pneumoniae, E. coli,* and *C. albicans* when treated with concentrations ranging from 600 µg/ml to 1000 µg/ml. Similarly, Abdel-Rahman

Table 1: Represents the green synthesis of different types of NPs from *M. oleifera*.

NPs	Part used	Solvent used	Technique used	Extraction Time	Bacterial Species	Mode of action	References
AgNPs	Leaf	Distilled water	Biogenic	1 hr	*E. fergusonii, C. violaceum, S. marcescens*	Suppress biofilm formation	Haris and Ahmad 2024
ZnONPs	Gum	Aqueous	Biogenic	-	*E. coli, S. aureus,*	Disrupts bacterial membrane, intracellular metabolic pathways, trigger oxidative stress	Irfan et al. 2021
MgONPs	Leaf	Distilled water	Biogenic	20 min	*S. aureus, E. coli*	Inhibits bacterial growth	Fatiqin et al. 2021
FeNPs	Seed	95% Ethanol, 0.1 M NaCl	Biogenic	30-45 min	*E. coli* O157	Interaction of "+" charged Fe ions with "-'' charged bacterial membrane causing bacteriostatic effects.	Katata-Seru et al. 2018
CaONPs	Leaf	Deionized water	Biogenic	3 hrs	*E. coli, S. aureus*	Bacteriostatic	Jadhav et al. 2022
La_2O_3NPs	Leaf	Water, Ethanol	Biogenic	30 min	*B. subtilis, E. faecalis, S. aureus, E. coli, P. aeruginosa, S. typhimurium*	Bacteriostatic	Shalaby et al. 2022
AuNPs	Seed	$AuCl_3$ solution	Biogenic	24 hrs	*E. coli, S. aureus*	Inhibits bacterial growth by inducing oxidative stress and apoptosis.	Bouttier-Figueroa et al. 2024
SeNPs	Leaf/ branch	Distilled water	Biogenic	52 hrs	*L. monocytogenes, C. diphtheriae*	Inhibits bacterial growth by cell wall damage and excessive oxidative stress.	Ao et al. 2022
CuS: Co NPs	Leaf	Deionized water	Biogenic	8 hrs	*B. cereus*	Blockage of DNA replication and protein synthesis due to interference by released metal ions	Karthika et al. 2023
CuS: Ni NPs	Leaf	Deionized water	Biogenic	8 hrs	*B. cereus*	Same as above	Karthika et al. 2023

et al. (2022) revealed that Moringa-based AgNPs bind with the phosphorus groups of DNA of *S. aureus*, *B. subtilis*, *S. marcescens*, and *E. coli*. This binding interpreted their replication cycle and caused mortality.

Inhibition of bacterial biofilm

Bacterial biofilm is described as a microbial community enclosed in extracellular polymeric substances (Funari and Shen 2022). A biofilm consists of a single microbe or a mixture of yeasts, bacteria, protozoa, fungi, and archaea. Bacterial biofilm is responsible for major global health issues, including antibiotic resistance, host immunity, and other outside stressors (Zhao et al. 2023). However, many studies related to the antibacterial activity of Moringa revealed its ability to exhibit a bacteriostatic effect by inhibiting the formation of biofilm by disrupting the extracellular polymeric substances that stabilize the biofilm (Oliveira et al. 2023). Fontana et al. (2023) reported the antibacterial activity of *M. oleifera* bioactive components by inhibiting the development of biofilm by suppressing the biofilm matrix synthesis in *Xanthomonas campestris*. Soraya et al. (2022) stated that 12.5% and 6.25% concentration levels of 96% ethanolic extract of *M. oleifera* leaves were most effective in inhibiting the development of biofilm in *Streptococcus mutans*. Haris and Ahmad (2024) reported that *M. oleifera*-derived AgNPs showed antibacterial activity through suppressing the formation of biofilm by interfering with the quorum sensing in *E. fergusonii*, *Chromobacterium violaceum*, and *Serratia marcescens* (Rueangsri et al. 2025).

Antiparasitic activity of Moringa and its derived NPs

Morinaga and its derived NPs have been documented as potential antiparasitic agents against different species of taxonomic groups, including Cestodes (Hatwiko et al. 2025), Nematodes (Geldenhuys 2023), and Protozoa (Elbarbary et al. 2023; Rashid et al. 2024). The bioactive components of Moringa inhibit the growth and reproduction of parasites by penetrating the cell via disrupting the structural integrity of the cell membrane (Nishi et al. 2021), followed by the generation of excessive oxygen radical species (Hamad et al. 2023) leading to the denaturation of essential proteins and enzymes and fragmentation of genome (Saad El-Din et al. 2023; Kanwal et al. 2024). Various studies confirmed that Moringa extract not only lessened the parasitic loads but also improved the physical condition of the host without causing harmful effects (Pedraza-Hernández et al. 2021). Furthermore, it is documented that Moringa-synthesized NPs enhance their anthelminthic efficacy by offering improved drug delivery and bioaccessibility (Ilavarashi et al. 2019). Despite this fact, very limited research has been conducted in this field, highlighting the need for future studies to explore their broad therapeutic potential. Their mechanism of action against parasites has been given in Figure 3.

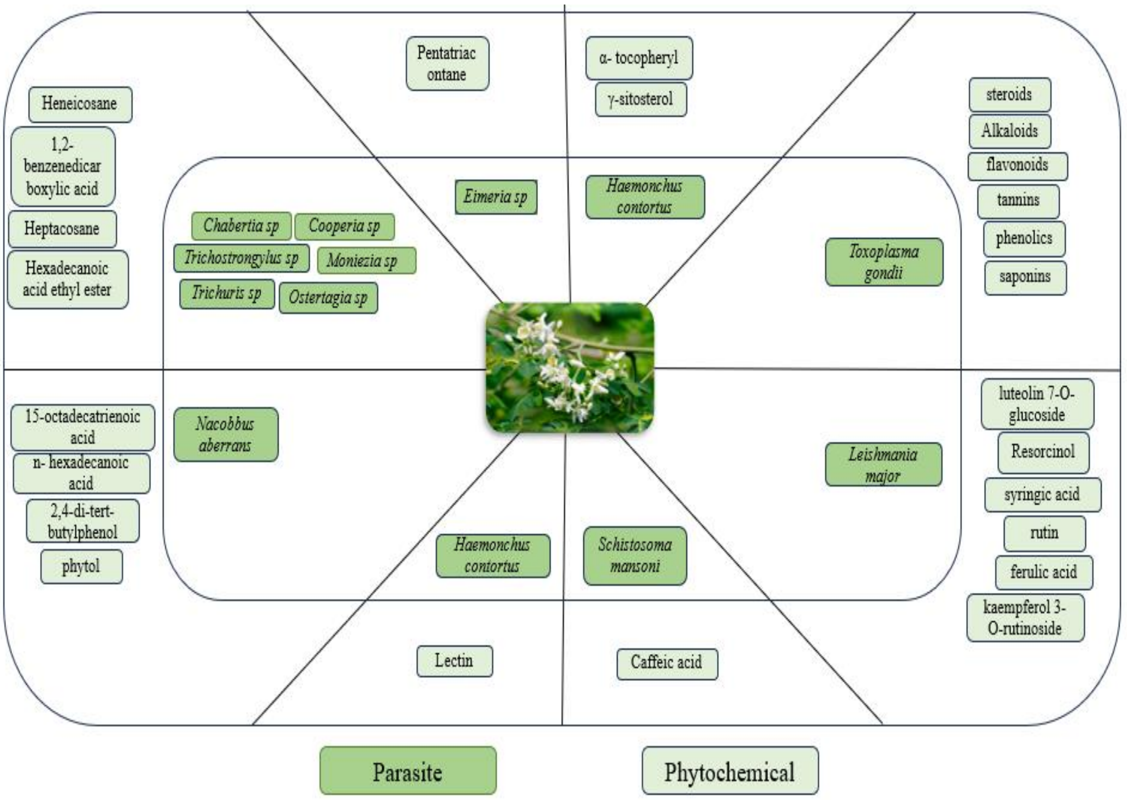

Fig. 3: Different phytochemicals of Moringa target different species of parasites.

Moringa and Moringa-derived phytochemicals and NPs reduced the parasitic burden by inhibiting parasitic stages, inhibition of egg production and hatching, and by directly killing the adult stage of the parasite.

Inhibition of parasitic stages

Moringa bioactive components exhibit antiparasitic activity by interfering with its reproductive stages. For instance, Hammi et al. (2020) revealed that *M. oleifera* ethanolic leaf extract targeted the amastigote and promastigote stages of *Leishmania major* when treated in the macrophage cell line Raw 264.7 with IC_{50} values of 9.31 ± 0.72 µg/ml and 6.87 ± 0.32 µg/mL, respectively. Similarly, Kandil et al. (2024) reported a 72% reduction in the *T. saginata* cysticerci count and size when treated with the methanolic seed extract of *M. oleifera* in Mice (*BALB/c*) at 150 mg/kg. Another study conducted by Wihanto et al. (2023) revealed the antiparasitic effect of bioactive compounds of *M. oleifera*, especially quinoline alkaloids, against *Toxoplasma gondii* when treated with 500 mg/kg and 1000 mg/kg ethanolic leaf extract. It inhibited the tachyzoite replication by the interaction of alkaloids with nucleotide pairs of the DNA, resulting in genetic mutations and ultimately disrupting the reproductive cycle (Rashid et al. 2024). Moreover, Medeiros et al. (2023) reported the antiparasitic effect of the bioactive component, lectin, of *M. oleifera* seed extract against *Haemonchus contortus* in *Rattus norvegicus* albinus when treated with 5 mg/kg, 2.5 mg/kg, and 1 mg/kg. All three concentrations proved effective in reducing the parasitic larval loads, however, 5 mg/kg was also observed for its toxic effects on the organs of the tested animal.

Reduction or Inhibition of eggs

Moringa and Moringa NPs reduce the parasitic load by inhibiting egg production. For instance, Pedraza-Hernández et al. (2021) demonstrated the antiparasitic effects of the hydroalcoholic leaf extract of *M. oleifera* on *Ostertagia sp.* and *Trichuris sp.* in goats. The phytochemicals, including hexadecanoic acid ethyl ester, heneicosane, and pentatriacontane, not only decreased their egg count but also improved the host's health. Konmy et al. (2023) reported the antiparasitic activity of the leaf extract of *M. oleifera* against the protozoan *Eimeria magna* and *E. media* in rabbits. The reduction in parasitic load was dose-dependent. Therefore, 95.43%, 88.26%, and 65.83% oocyst reduction was observed at 1000 mg dose, 500 mg, and 250 mg/kg, respectively. Additionally, Páez-León et al. (2022) revealed that the ethyl acetate leaf extract of *M. oleifera* showed considerable efficacy against *Nacobbus aberrans* and *H. contortus*. The results showed a significant reduction in egg inhibition and larval mortality when treated with a concentration of 5 mg/mL and 10 mg/mL, respectively (Tahir et al. 2024).

Moreover, Ilavarashi et al. (2019) revealed the excellent efficacy of *M. oleifera*-derived AgNPs, which exhibited anthelminthic activity against Strongyloides in ruminants and showed an 80.59% reduction in egg hatching when treated with effective concentrations of 8 mg/ml (Mehwish et al. 2024).

Killing of adult parasites

Moringa can exhibit antiparasitic activity by killing the adults. Huang et al. (2023) reported the bacteriostatic effect of Mop2 protein extracted from the seed of *M.*

oleifera in *S. aureus.* Mop2 protein reduced the adult population through the fragmentation of DNA by the activation of endonucleases. Moreover, Saad El-Din et al. (2023) revealed the synergistic effect of *M. oleifera* aqueous leaf extract with praziquantel therapy against *Schistosoma mansoni* in Albino CD-1 mice. Results showed excellent efficacy through significant reduction in adult parasitic loads due to disruption of the reproductive cycle of the parasite when treated with effective concentrations of 300 mg/kg and 150 mg/kg of PZQ and MOL, respectively. Similarly, Apsari et al. (2024) revealed the moderate efficacy of 70% ethanolic leaf extract of *M. oleifera* against the protozoa *Plasmodium berghei* in BALB/c mice by reducing its adult parasitic loads in different organs in an *in vitro* study. This investigation was done to examine the antimalarial activity of *M. oleifera* (Wahid et al. 2025).

Various antiparasitic properties of different phytochemicals of Moringa extracts are given in Table 2.

Future perspective

Despite the potential bacteriostatic and antiparasitic attributes of *M. oleifera* and its originated NPs, extended study is required for a complete understanding of their mode of action, effectiveness, and potential uses in the health care system. While notable investigations have been done on the bactericidal and bacteriostatic effects of Moringa extracts and it's derived NPs, insufficient data is present on their antiparasitic activity, especially against helminthic and protozoan. Upcoming studies should be based on enhancing nanoparticle fabrication, increasing their efficacy, and assessing their biosafety in human and animal models. Moreover, proper clinical studies are required to discover their efficacy in contrast to conventional anthelminthic drug treatments. Additionally, the studies on the combined effect of Moringa and available medication could be used to develop next-generation therapeutics. Advancement in this field could be achieved by working on all the related fields, including nanoscience, parasitology, and pharmacology.

Table 2: Antiparasitic effect of various phytochemicals obtained from Moringa

plant	Phytochemicals	Part	Technique	Extraction Time	Type of Parasite	Parasite Species	Host	Results	Efficacy	Efficiency	References
M. oleifera	Heneicosane, 1,2-benzenedicarboxylic acid, Heptacosane, Pentatriacontane	Leaf	Solvent extraction	72 hrs	Protozoa, nematode, cestode	*Eimeria sp., Ostertagia sp., Trichuris sp., Moniezia sp., Cooperia sp.*	Goat	Reduced egg count	Excellent	90%	Pedraza-Hernández et al. 2021
	9, 12, 15-octadecatrienoic acid, n-hexadecanoic acid, 2, 4-di-tert-butylphenol, phytol, γ-sitosterol and α-tocopheryl acetate.	Leaf	Solvent extraction	-	Nematode	*H. contortus, N. aberrans*	-	Increased larval mortality, Suppressed egg hatching	Excellent	90%	Páez-León et al. 2022
	Resorcinol, luteolin 7-O-glucoside, syringic acid, rutin, ferulic acid, kaempferol 3-O-rutinoside	leaf	Ultrasound-assisted extraction	20-40 min	protozoa	*L. major*	Macrophage cell line (Raw 264.7)	Antiamastigote and antipromastigote activity	Excellent	100%	Hammi et al. 2020
	-	Seed	Maceration	48 hrs	Cestode	*T. saginata*	Mice (*BALB/c*)	Decreased cysticerci count and size.	Excellent	72%	Kandil et al. 2024
	Alkaloids, flavonoids, phenolics, steroids, saponins, tannins	Leaf	Maceration	24 hrs	protozoa	*T. gondii*	DDY mice	Decreased parasitic load.	Moderate	60%	Wihanto et al. 2023
	Caffeic acid	leaf	Maceration	24 hrs	Trematode	*S. mansoni*	Albino CD-1 mice	Reduced larval count	Excellent	90%	Saad El-Din et al. 2023
	Lectin	Seed	Chromatography	16 hrs	Nematode	*H. contortus*	Wistar rats	Reduced larval count.	Excellent	70%	Medeiros et al. 2023
	-	leaf	Solvent extraction	2 hrs	Protozoa	*E. magna, E. media*	Rabbits	Reduced oocyst count	Excellent	80%	Konmy et al. 2023
	-	Leaf	Maceration	3 Days	Protozoa	*P. berghei*	BALB/c mice	Reduced oocyst count	moderate	50%	Apsari et al. 2024

Conclusion

The considerable antibacterial and anthelminthic properties of Moringa and its synthesized NPs bring them into the category of promising medicinal agents. The chemical bioactive components of Moringa are the main reasons for its bacteriostatic and antiparasitic potency. Additionally, NPs improve stability, solubility, and absorption, as well as drug delivery and bioavailability. Moreover, a lot of research has been conducted against various bacterial species and parasites to better understand the potential bactericidal and ovicidal mode of action of the plant. However, at the same time, further research is needed to study the optimum effects of green synthesized NPs formulated through different extraction procedures in comprehensive *in vivo* settings. Moringa-based NPs provide an appropriate and herbal substitute against antibiotic resistance and the challenges of traditional anthelminthic drugs. Persistent scientific investigations and therapeutic assessment will be necessary to harness its medicinal efficacy for human and animal healthcare uses.

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