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MORINGA MEDIATED ZNO NANOPARTICLES: ANTIMICROBIAL, ANTICANCER, AND EMERGING BIOMEDICAL APPLICATIONS

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Abstract *The production of metal oxide nanoparticles using the plant extracts as a sustainable option compared to traditional chemical methods. Moringa oleifera, abundant in phytochemicals, has attracted recent interest as a biological resource for the production of zinc oxide nanoparticles (ZnO NPs). This review analyzes fabrication of ZnO nanoparticles from various parts of M. oleifera, such as seeds, leaves, roots, flowers, and bark exudates, and assesses the impact of phytochemical composition on nanoparticle size, morphology, crystallinity, and biological activity. Nanoparticles range from 10–60 nm and mainly display spherical or hexagonal wurtzite patterns. Nanoparticles from seeds consist of smaller dimensions because of resilient protein-based capping processes, while extracts from leaves are most intensively researched due to high levels of flavonoids and phenolics. The review examines antimicrobial, antifungal, and anticancer activities. Regardless of the promising biomedical potential, gaps still exist in antiviral research, in vivo safety assessments, and uniform synthesis procedures. Future research should focus on translational and mechanistic validation studies to support clinical uses.*

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Introduction

Moringa oleifera is a root of many minerals, amino acids, vitamins, and antioxidants, and its application in traditional medicine and nutrition has a long tradition (Murali et al., 2021). These are the bioactive compounds in the plant: polyphenols, flavonoids, alkaloids, terpenoids, proteins, and carbohydrates. These compounds are present in almost all parts of the plant, including roots, leaves, seeds, flowers, bark, and gum (Murali et al., 2021). Moringa extracts are able to serve as a natural synthesizer of metal and metal oxides, e.g., ZnO, silver, gold, titanium oxide, and iron oxide, and confer biological functions to the end product (Li et al., 2020; Murali et al., 2021). ZnO nanoparticles (ZnO NPs) are among the most commonly researched metal-oxide nanomaterials because of their high surface area and semiconductor properties, and the capability to produce reactive oxygen species (ROS) and release Zn^{2+} ions (Murali et al., 2021). The broad biomedical effects of these features are antibacterial, antifungal, anticancer, antioxidant, anti-inflammatory, antiviral, wound-healing, and drug-delivery uses (Hussien et al., 2025; El-Saadony et al., 202). ZnO NPs are relatively cost-effective and display moderate biocompatibility at moderate dosage, as well as are generally regarded as safe in certain applications, in comparison to many other types of inorganic nanomaterials (Motelica et al., 2023). Conventional physical and chemical methods for producing ZnO nanoparticles (ZnO NPs) often require elevated temperatures, organic solvents, and hazardous reducing or stabilizing agents, leading to the formation of toxic byproducts and limiting their potential for clinical application (Okaiyeto et al., 2024; Hussien et al., 2025;. Plant extract-mediated green synthesis is a more viable, scalable, and sustainable method of synthesis as compared to the HbF-type method. Under this system, the phytochemicals that occur naturally are simultaneously reducing, stabilizing, and capping agents, and therefore no synthetic chemicals are needed. Moreover, phytochemical modification of plant-based ZnO nanoparticles (ZnO NPs) is expected to boost them.

Different parts of the Moringa plant contain distinct phytochemical compositions that influence ZnO nanoparticle nucleation and growth, thereby affecting particle size, morphology, crystallinity, and surface characteristics (El-Saadony et al., 2024). ZnO nanoparticles have been synthesized using Moringa leaves, seeds, flowers, bark, and gum. For instance, seed extracts have produced ZnO nanoparticles with high zinc purity and minimal residual carbon, and Moringa-mediated ZnO has demonstrated notable antifungal activity against plant pathogens (Akhras et

al., 2025). Since nanoparticles are highly sensitive to antimicrobial and anticancer activity based on their size, shape, and surface traits, rational selection of the Moringa part is a design parameter to guide the activity (El-Saadony et al., 2024; Murali et al., 2021). Unlike previous reviews that broadly discuss plant-mediated ZnO nanoparticles, this review critically compares nanoparticle characteristics derived from different parts of Moringa oleifera, evaluates synthesis parameters controlling morphology, and highlights unresolved mechanistic and toxicological questions relevant for biomedical applications.

Phytochemical Composition of Moringa Plant Parts and Their Role in ZnO Formation

Leaf Extract–Mediated Synthesis

The most commonly used plant component to prepare nanoparticles of ZnO is the Moringa leaf extract because it is rich in proteins, polyphenols, flavonoids, and other bioactive molecules that serve as natural reducing agents and capping agents in forming nanoparticles (Huq et al., 2023; Murali et al., 2021; Singh et al., 2023). Quercetin and kaempferol are some of the flavonoids, phenolic acids, vitamins, and proteins that especially occur in the leaves of Moringa oleifera and that define the size of the ZnO nanoparticle and the coating that results in the antimicrobial and potential therapeutic activity (Murali et al., 2021). These polyphenols, flavonoids, vitamins, proteins, lipids, and polysaccharides, which are present in leaves, seeds, flowers, roots, and gums, can not only reduce zinc salts to ZnO but also leave them on the surface of nanoparticles as a natural coating (Murali et al., 2021). The hydroxyl, carboxyl, and amine groups of these molecules bind the zinc ions and help in the formation of ZnO, and are carried with it as a soft organic shell. In plant-based ZnO nanoparticle systems, a direct association of polyphenols and other phytochemicals tends to be a favorable association of smaller and more uniform particles. Smaller nanoparticles tend to be more antibacterial and, in other cases, anticancer due to their greater surface area and ability to react (El-Saadony et al., 2024; Murali et al., 2021; Okaiyeto et al., 2024). Additionally, a sufficient organic coating based on biomolecules of vegetative sources can aid in averting the aggregation of particles, thus maintaining the stability of nanoscale and preserving biological activity (El-Saadony et al., 2024).

Synthesis

Normally, fresh or dried Moringa leaves are the ones that are extracted with water or ethanol, and the extracted material is then combined with the precursors of zinc, e.g., $Zn(NO_3)_2$ or $Zn(CH_3CO_2)_2$. The reaction is done at mild heating (around 60–80 °C) in several hours, usually at neutral or slightly alkaline pH (Murali et al., 2021; Huq et al., 2023; Singh et al., 2023). The phytochemicals of plants contribute to the production of nanoparticles as reducing and stabilizing (capping) agents in alkaline conditions since ZnO is favored to grow (Li et al., 2020; Pareek et al., 2023; Murali et al., 2021; Okaiyeto et al., 2024). Leaf-mediated ZnO nanoparticles (ZnO NPs) are widely spherical with sizes of about 20–60 nm, and they are usually hexagonal crystal structures of wurtzite with confirmation through X-ray diffraction analysis (XRD) and electron microscopy analysis (Huq et al., 2023; Murali et al., 2021; Purushotham et al., 2025; Singh et al., 2023). The plant-mediated ZnO nanoparticles (ZnO NPs) in general are between 10 and 60 nm in size, are mostly in the wurtzite phase, and are mostly spherical or hexagonal in shape (El-Saadony et al., 2024; Li et al., 2020; Okaiyeto et al., 2024). The presence of the ultraviolet visible absorption peak, ~380 nm, in the range of 350–380 nm and a clear Zn–O band at 400–500 cm^{-1} confirms the production of ZnO, whereas the presence of broad O–H and C=O bands is observed to indicate polyphenol presence and flavonoid capping presence as well (Huq et al., 2023; Murali et al., 2021; Purushotham et al., 2025). Negative zeta potential values and high colloidal stability of similar systems are attained by the presence of dissociated phenolic and carboxyl groups on the surface of the plant–ZnO (Huq et al., 2023; Purushotham et al., 2025; Singh et al., 2023). The existence of plant-based chemicals, specifically phenolic acids and flavonoids, controls the nucleation and growth process, which plays a role in the regulation of size and thus prevents aggregation, which is essential in antimicrobial and anticancer action (Huq et al., 2023; Murali et al., 2021; Singh et al., 2023). The leaf-based ZnO systems are closely related to antibacterial, antifungal, antioxidant, and wound-healing-relevant plant-mediated ZnO systems and usually serve as models of coating and dressing (El-Saadony et al., 2024; Li et al., 2020; Okaiyeto et al., 2024; Murali et al., 2021; Pareek et al., 2023). The leaf-based routes are seen as the most reproducible and scalable, as the annual production of the leaf and low-cost and simple extraction protocols can be taken into consideration (Huq et al., 2023; Purushotham et al., 2025; Tao et al., 2025).

Seed Extract–Mediated Synthesis

Having fewer research studies and possessing a distinct phytochemical environment with proteins, lipids, glucosinolates, terpenoids, alkaloids, flavonoids, and other nitrogen-containing compounds are Moringa seed extracts (Pareek et al., 2023; Purushotham et al., 2025; Tao et al., 2025). Stable structures or long structures often form during the synthesis of plant-based ZnO by using protein-rich extracts and may be used in microbicidal or photocatalytic applications, and can be antimicrobial (El-Saadony et al., 2024; Okaiyeto et al., 2024). Proteins and amino acids can be utilized as the reducing and structure-directing agents (Pareek et al., 2023; Okaiyeto et al., 2024).

Synthesis

The process of extraction normally demands vigorous grinding and occasionally natural co-solvents with the aim of solubilizing both polar and non-polar constituents (Tao et al., 2025). Aqueous or organic seed extracts are combined with zinc salts at moderate heating; reaction times are rather long compared to leaves due to slower progress, which implies slower reduction kinetics (Tao et al., 2025; Okaiyeto et al., 2024). Green ZnO produced in plant seeds is, in most cases ~50 nm and spherical to hexagonal (El-Saadony et al., 2024; Okaiyeto et al., 2024). Non-spherical or anisotropic morphologies, such as nanorods or nanowires, can also be observed in seed-derived ZnO nanoparticles (ZnO NPs) in corresponding plant systems because proteins can also serve as structure-directing agents and selectively bind specific crystal faces (Huq et al., 2023; Purushotham et al., 2025). A basic analysis of Moringa-seed-bound ZnO nanoparticles (ZnO NPs) showed high amounts of zinc content (Zn was found to be predominant, approximately 87–100 wt%, and O was found to be approximately 10–11 wt% with C being approximately 3–4 wt%), indicating the successful conversion and apparently low amounts of organic loading upon the particle surface. Caps with a high protein content are supposed to give a high amide band (1650 and 1550 cm^{-1}) in FTIR spectra and steric hindrance to increase the colloidal stability, whereas lipids and fatty acids have the potential to affect hydrophobicity and cellular absorption (Huq et al., 2023; Purushotham et al., 2025; Tao et al., 2025). In general, seed-mediated ZnO exhibits antibacterial and photocatalytic activities (Pareek et al., 2023; Okaiyeto et al., 2024). Moringa-seed ZnO has high levels of Zn and low levels of carbon, which means that it has good antimicrobial and photocatalytic potential (Okaiyeto et al., 2024; Pareek et al., 2023). The unique coating structure results in biological activity profiles potentially different from medical.

Root Extract–Mediated Synthesis

Moringa root extracts are even less investigated, yet reviews of green ZnO indicate that overall, the root-based plant extracts can yield very crystalline ZnO nanoparticles (ZnO NPs) with high antimicrobial activity (Huq et al., 2023; Purushotham et al., 2025; Tao et al., 2025). Moringa roots contain elements of phenols and alkaloids as well as those associated with lignin (Pareek et al., 2023). Stronger conditions are typically applied to extract roots (by increasing temperature and increasing boiling) to extract phenolics, alkaloids, and terpenoids, which are attached to lignin (Huq et al., 2023; Tao et al., 2025). Hot aqueous root extract is reacted with zinc salts; phenols and alkaloids reduce and chelate Zn^{2+} (El-Saadony et al., 2024; Okaiyeto et al., 2024; Pareek et al., 2023).

Structural Characteristics

Many root-mediated ZnO systems produce nanoparticles of zinc oxide that are highly crystalline wurtzite in nature and have a diameter of between 15–40 nm (El-Saadony et al., 2024; Okaiyeto et al., 2024; Li et al., 2020). Root-mediated ZnO nanoparticles (ZnO NPs) in analogs are reported to be sharp-peaked, well-dispersed spherical particles within the 15–40 nm size range, suggestive of high crystallinity and phase purity, which is attributed to the high antimicrobial efficacies (Huq et al., 2023; Da Silva et al., 2019; Purushotham et al., 2025). Common in FTIR are phenolic O–H, C=O, and N–H groups that are typical of a combination of polyphenols and alkaloids on surfaces, which are reducing and stabilizing agents (Huq et al., 2023; Tao et al., 2025). Roots and green ZnO are likely to exhibit a high degree of antibacterial response; high crystallinity and size are connected with improved ROS-mediated bacterial killing (Li et al., 2020; Okaiyeto et al., 2024; Pareek et al., 2023). Moringa roots are pharmacologically active and antimicrobial (ZnO), which is promising, but few experimental studies have been done on them. Roots may be utilized to generate particles with a high level of antibacterial effectiveness, but the destructive harvesting principle, low biomass, and the risk of inducing soil contamination make roots less practical when comparing them to leaves and seeds to be utilized in a sustainable, large-scale biomedical application (Huq et al., 2023; Tao et al., 2025; Purushotham et al., 2025).

Variations in Moringa-Mediated ZnO Synthesis

Moringa oleifera leaf extracts are the most studied for ZnO nanoparticle synthesis and phenolic acids. These phytochemicals are natural reducing and capping agents under mild heating paired with alkaline conditions to produce crystalline ZnO NPs exhibiting strong antibacterial, antioxidant, photocatalytic, and promising anticancer activities (Matinise et al., 2017; Jadhav et al., 2022; Sarwar et al., 2025; Perumalsamy et al., 2024). Seed-derived ZnO nanoparticles (ZnO NPs) tend to be smaller (~15 nm) with diverse morphologies, including nanorods, due to proteins and amino acids directing growth during synthesis. This phenomenon is largely attributed to the unique biochemical composition of Moringa seeds. Seeds contain proteins, peptides, fatty acids, and polypeptides known for their natural coagulating properties. During growth and nucleation, they bind to the surface of nanoparticles and act as caps and stabilizers. These strong surface interactions could restrict uncontrolled crystal proliferation that leads to the making of smaller and more evenly spread NPs for medical usage (Kalaiyarasi et al., 2022; Perumalsamy et al., 2024; Ngom et al., 2020). Additionally, proteins present in seed extracts can provide multiple binding sites for zinc ions, creating a more controlled nucleation process. As a result, nanoparticle growth is limited at earlier stages, producing smaller particles with narrower size distributions. This highlights the importance of plant-part-specific phytochemistry in determining nanoparticle characteristics and applications. Flower-based Moringa ZnO

nanoparticle data remain limited but indicate antibacterial potential (Ngom et al., 2020; Perumalsamy et al., 2024). Overall, Moringa-derived ZnO nanoparticles (ZnO NPs) combine eco-friendly green synthesis features with multifunctional bioactivities driven by their phytochemical composition and nanoparticle size/shape (Garza-Alonso et al., 2021; Kalaiyarasi et al., 2022; Jadhav et al., 2022; Perumalsamy et al., 2024; Matinise et al., 2017; Parven et al., 2025; Shashikala et al., 2024; Sarwar et al., 2025).

Table 1. Comparative table summarizing plant part-mediated green synthesis of ZnO nanoparticles (ZnO NPs), highlighting phytochemicals, synthesis characteristics, and bioactivities

Plant Part	Approx. NANOPARTICLE Size / Shape	Phytochemicals	Green Synthesis Features*	Main Bioactivities	references
Leaves	~15 nm; nanostructures modified by phytochemicals	Flavonoids, phenolics	Aqueous leaf extract + zinc nitrate; mild heating; phytochemicals as reducing/capping agents	Photocatalytic oxidation of erythrosine dye; antibacterial activity	Parven et al., 2025
	~52 nm; hexagonal wurtzite; flower-like morphology	Phenolics, flavonoids, alkaloids, proteins, terpenoids	Eco-friendly biosynthesis using leaf extract; no toxic chemicals/high energy	Antibacterial and antioxidant activities	Sarwar et al., 2025
	~55 nm; spherical)	Polyphenols, flavonoids	Aqueous leaf extract; mild green synthesis	Hepatoprotective effect in rats; antioxidant enzyme restoration	El-Beltagi et al., 2024
	~50 nm; hexagonal wurtzite	Flavonoids, phenolics proteins, terpenoids	Ratios of leaf extract + zinc salts; confirmed by XRD, FTIR, EDX	Strong antibacterial activity (Gram+ and Gram–)	Shashikala et al., 2024
	~52 nm; hexagonal wurtzite	Flavonoids, phenolic compounds	Precipitation method using leaf precursor; UV-Vis, FTIR, SEM	Photocatalytic dye degradation; antibacterial (*B. subtilis*, *E. coli*)	Pal et al., 2018
Seeds	~15.3 nm; nanostructured	Alkaloids, flavonoids, steroids, glycosides, polyphenols, proteins, carbohydrates	Seed extract + zinc salts; moderate heating; phytochemicals stabilize/cap	Antimicrobial (bacteria/fungi); photocatalytic dye degradation; phytotoxicity modulation	Kalaiyarasi et al., 2022
	~13.9 nm; spherical	Oleic acid, proteins, polyphenols	Seed extract + zinc nitrate hexahydrate; chelating/reducing agent	Structural/optical properties for biomedical use; antimicrobial potential	Ngom et al., 2020
	-	Polyphenols, secondary metabolites	Seed extracts as reducing/capping agent	Antibacterial, antioxidant, anticancer	Perumalsamy et al., 2024
Roots	~15–40 nm, hexagonal wurtzite	Polyphenols, flavonoids	Aqueous root extract; mild eco-friendly synthesis; confirmed by UV-Vis, XRD, FTIR, SEM, EDX	Strong antibacterial activity; high purity/crystallinity	Espenti et al., 2020
Flowers	~13.2 nm; hexagonal wurtzite	Quercetin	Flower extract as chelating/reducing agent; band gap ~3.12 eV	Photocatalytic activity; antibacterial potential	Ngom et al., 2020

	~50 nm; spherical	Various phytochemicals	Hexagonal wurtzite; high surface area (~77 m²/g); UV-vis bandgap 3.36 eV	Antioxidant, anti-acne, antibacterial (*E. coli*, *S. aureus*)	Bhalla et al., 2022
	~13.2 nm	Quercetin	Biosynthesis via natural extracts; crystalline ZnO nanoparticles (ZnO NPs); photoluminescence bands	Structural/optical properties; biomedical potential	Ngom et al., 2020
Gum / Exudate	40–70 nm, irregular to crystalline	Complex polysaccharides	Aqueous gum solution with zinc salts; mild heating; viscous polysaccharides form thick capping layers stabilizing crystallinity	High colloidal stability; antibacterial effects; antioxidant potential; relevance for tissue engineering	(Perumalsamy et al., 2024; Jadhav et al., 2022)

*Synthesis conditions summarized from broad plant-mediated ZnO reviews; typical ranges are not Moringa-specific in all cases

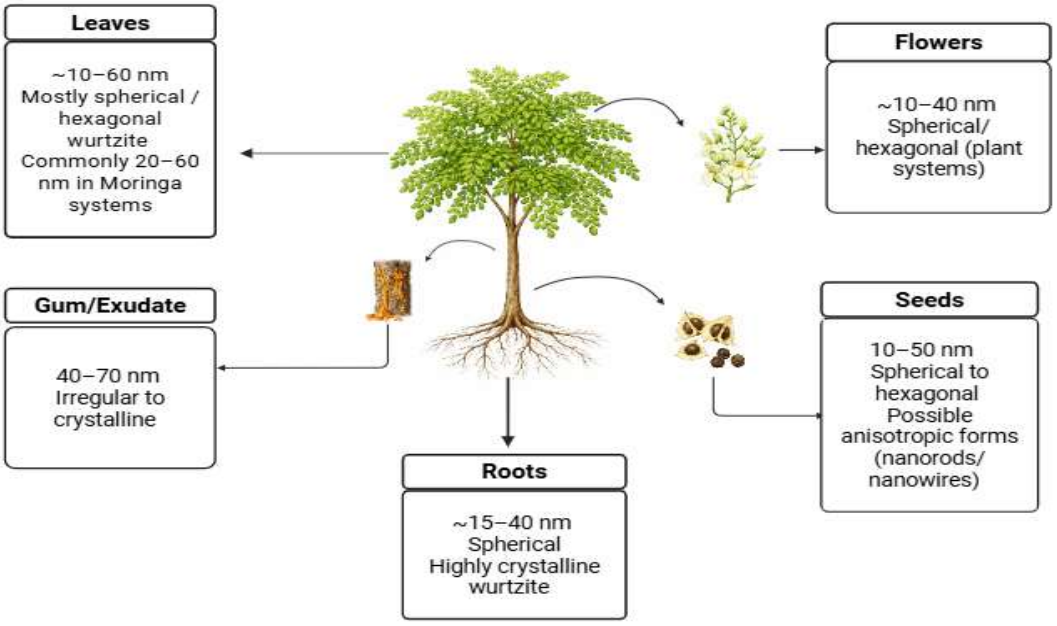

Figure 1: Schematic diagram showing nanoparticle size and morphology derived from different *Moringa oleifera* plant parts (flowers, leaves, seeds, roots, and gum/exudate)

Antibacterial and Antifungal Properties of Moringa-Mediated ZnO nanoparticles

Inhibiting Effect Against Bacteria

Mechanisms

ZnO NPs produced using the leaf of Moringa have a broad spectrum antibacterial action against Gram-negative and Gram-positive bacteria, and inhibition zones against disease-causing microbes like *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Bacillus subtilis* are 15–17 mm at higher doses (Sarwar et al., 2025). The organically synthesized ZnO NPs are often found to be better than or as effective as traditional antibiotics and chemically synthesized ZnO because they are smaller in size and have a greater surface area relative to their volume, and because they contain bioactive phytochemical capping by Moringa extracts, which is better at stabilizing them and interacting with bacterial cells (Irfan et al., 2021; Abel et al., 2021; Pal et al., 2018; Shashikala et al., 2024). These antibacterial mechanisms are disruption of bacterial membranes; release of cellular contents; formation of ROS, with H_2O_2, •OH, and superoxide anions (O_2^-); destabilization of lipids, proteins, and DNA; and release of Zn^{2+} ions, which alter respiration of bacteria and enzyme activity (Hayat et al., 2022; Mendes et al., 2021; Shashikala et al., 2024). Moreover, the same nanoparticles prevent the production of biofilm,

which is important to bacterial resistance. (Agrawal et al., 2023; Hayat et al., 2022; Shashikala et al., 2024). Tens to several hundred micrograms per milliliter in minimum inhibitory concentrations (MICs) are the typical ranges of plant-mediated ZnO nanoparticles, where smaller and well-capped particles demonstrate greater antibacterial activity and higher biofilm-disruption capabilities (Agrawal et al., 2023; Mendes et al., 2021; Hayat et al., 2022). Reviews note that ZnO nanoparticles derived from Moringa have the capability of being used as alternative antimicrobial agents in biomedical and food applications because of their strong activity and environmentally friendly synthesis (Bhalla et al., 2022; Irfan et al., 2021; Shashikala et al., 2024; Sarwar et al., 2025).

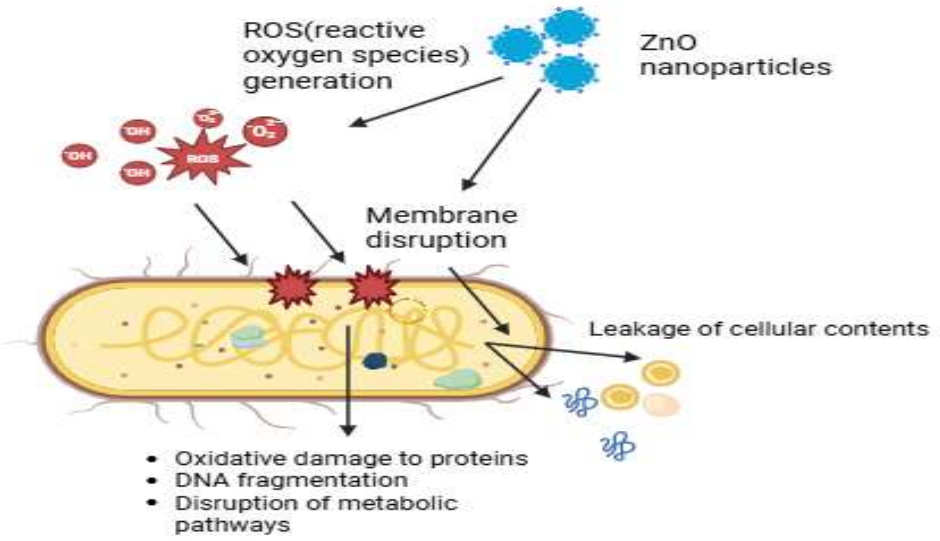

Figure 2: Schematic diagram illustrating antibacterial mechanisms of ZnO nanoparticles

Antibacterial Activity

Table 2: Comparative table summarizing the activity of biosynthesized ZnO nanoparticles (ZnO NPs) against bacteria from different *Moringa oleifera* parts and systems, showing tested bacteria, assays, and inhibition outcomes

NANOPARTICLE System / Plant Part	Bacteria Tested	Assay	Key Results	Reference
Moringa leaf-derived ZnO NPs	*Staphylococcus aureus* *Pseudomonas aeruginosa* *Escherichia coli* *Bacillus subtilis*	Agar well diffusion (ZOI)	Inhibition zones: 15–17 mm at 100 µg	Sarwar et al., 2025
Moringa oleifera gum-based ZnO NPs	*E. coli* *S. aureus* MRSA	Kirby-Bauer disc diffusion assay	MIC = 10 µg/disc. *E. coli*: 21–22 mm *S. aureus*: 20–21 mm MRSA: 16–17 mm.	Irfan et al., 2021
Leaf extract ZnO NPs	*Pseudomonas sp.* *Bacillus sp.*	Antibacterial assay (ZOI)	Highest inhibition zones observed against *Pseudomonas* and *Bacillus*	Shashikala et al., 2024
Ag-doped ZnO nanostructure (leaf extract)	*S. aureus* *E. coli* *P. aeruginosa* MRSA, others	Disc diffusion	Maximum inhibition zone: 17 mm (*S. aureus*) Strong antibacterial activity overall	Swati et al., 2020
Leaf extract ZnO NPs (green synthesis)	*S. aureus* *E. coli*	Disc diffusion / MIC	ZOI: up to 26.75 mm (*E. coli*) 30 mm (*S. aureus*) at 200 µg/mL MIC = 500 µg/mL	Bhalla et al., 2022
Leaf extract ZnO NPs (precipitation method)	*B. subtilis* *E. coli*	Disc diffusion	Antibacterial activity confirmed Average grain size ~52 nm	Pal et al., 2018
ZnO/PVA nanocomposite (leaf extract template)	*E. coli* *S. aureus*	Disc diffusion	Antibacterial inhibition efficienc aureus) and *aureus*), ≈ 15–18 mm (*E. coli*).	Dejen et al., 2020

ZnO NPs (MFPE synthesis)	*E. coli* *S. aureus*	Well diffusion method	Zone of inhibition ≈ 6 mm for both *S. aureus* and *E. coli*.	Surendra et al., 2016
Biosynthesized ZnO NPs (aqueous leaf extract)	*S. aureus* *E. coli*	Disc diffusion method	ZOI: up to 24.3 mm (*S. aureus*) Up to 11.57 mm (*E. coli*) Activity increased with concentration (3–9%)	Rhamdiyah & Maharani, 2022
ZnO NPs (biosynthesized from *M. oleifera* seeds)	**Gram-negative bacteria:** *Shigella flexneri*, *Salmonella typhi*, *Klebsiella pneumoniae*, *Proteus vulgaris*, *Vibrio cholerae*, *Pseudomonas aeruginosa* **Gram-positive bacteria:** *Bacillus subtilis* *Staphylococcus aureus*	Agar well diffusion method	Inhibition zones ranging from 11 to 30 mm. Greater activity against Gram-negative bacteria compared to Gram-positive bacteria	Kalaiyarasi et al., 2022

Antifungal Activity

Mechanisms

ZnO nanoparticles (ZnO NPs) derived using Moringa are antifungal agents that mainly act through various mechanisms. These nanoparticles produce ROS, including •OH, and superoxide anions (O_2^-), that create oxidative stress that destroys fungal cell membranes and proteins as well as DNA. ZnO nanoparticles have a small size and positive surface charge to promote their uptake by the fungal cells, which increases ROS generation and interrupts the integrity of the membrane, thus blocking spore germination and germ tube growth. Moreover, ZnO nanoparticles affect ergosterol biosynthesis, which is one of the main constituents of fungal cell membranes, further destabilizing the membrane and impairing its operation as well. The presence of a crystalline structure and surface functional groups of morphine phytochemicals of the nanoparticles is a contributing factor to their high affinity to fungal cells, which leads to increased antifungal activity against Candida species and filamentous fungi. All these outcomes cause the stopping of the growth and spore formation of fungi, which makes the ZnO nanoparticles formed with Moringa effective antifungal agents (Table 3) (Surendra et al., 2016; Abomuti et al., 2021; Obiazikwor and Ojeile, 2022).

Antifungal Activity

Table 3. Comparative table summarizing antifungal activity of Moringa oleifera extracts and ZnO nanoparticle systems, showing tested fungi, assays, and quantitative inhibition outcomes

NANOPARTICLE System / Plant Part	Fungi Tested	Assay	Key Quantitative Results	Reference
Ag-doped ZnO nanostructure from Moringa oleifera (leaf)	*Candida albicans*, *Sclerotinia sclerotiorum*, *Fusarium* spp., *Rosellinia necatrix*	Disc diffusion, growth inhibition	Inhibition zone: 18 mm for *C. albicans*; growth inhibition: 56.8% (*R. necatrix*), 34.78% (*Fusarium* spp.), 48.9% (*S. sclerotiorum*)	(Verma et al., 2020)
Mesoporous ZnO loaded with Moringa seed compound	*Candida albicans*, *Aspergillus niger*	Paper disc diffusion, broth dilution	MIC for *C. albicans*: 0.1% with mesoporous ZnO + compound; synergistic antimicrobial effect observed	(Jenish et al., 2022)
Moringa leaf-mediated ZnO nanoparticles	Pythium spp., *Fusarium* sp., *Aspergillus* sp. (from ginger soft-rot)	Kirby-Bauer disc diffusion, MIC	Effective inhibition of all tested phytopathogenic fungi; average NP size: 78 nm	(Ingle et al., 2024)
Moringa leaf/flower-mediated Ag/ZnO nanoparticles	*Pestalotiopsis mangiferae*	Radial growth inhibition	Significant reduction in fungal radial growth at low concentrations; potent fungistatic agent	(Jenish et al., 2022)
ZnO nanoparticles/mancozeb combinations using Moringa leaf extract	*Eurotium* sp. (cassava pathogen)	Food poisoning method	100% inhibition of *Eurotium* sp. at certain nanoparticle/mancozeb ratios	(Obiazikwor & Ojeile, 2022)

The tested fungal species, assay techniques, and quantitative inhibition results for various Moringa oleifera nanoparticles are compiled in this table. The data show that several strategies [Ag doping, mesoporous ZnO loading, and ZnO/mancozeb combinations] improve antifungal efficacy. In synergistic systems, inhibition zones ranged from 11 to 30 mm, and MIC values as low as 1% were found.

Antiviral Potential of Moringa-Mediated ZnO nanoparticles (ZnO NPs)

There has been a research gap, as the direct evidence of the ZnO nanoparticles produced by Moringa having antiviral activity has not yet been provided. Cassia javanica plant-derived ZnO nanoparticles have demonstrated the strongest antiviral properties against viruses like HSV-1 and Coxsackievirus B4 with an inhibition rate of 75.4 and 65.8 at 62.5 µg/mL, respectively (Almuhayawi et al., 2024). PEGylated ZnO nanoparticles (ZnO NPs) also have a high antiviral effect against the H1N1 influenza virus (~94.6% inhibition), which is higher than that of naked ZnO (Mandal et al., 2022). ZnO nanoparticles employ antiviral actions that are mostly associated with interacting with a virus, the formation of reactive oxygen species (ROS), and the interruption of the entry or replication of viruses (Mandal et al., 2022; Attia et al., 2021; Melk et al., 2021). Although it would be logical to assume that the Moringa-mediated ZnO nanoparticles (ZnO NPs) could have these antiviral properties because of the similarity in physicochemical properties and bioactive capping agents, the antiviral activity of such ZnO nanoparticles (ZnO NPs) in relation to morphine remains hypothetical without direct experimental data. Thus, specific research is required to prove or measure the antiviral effect of ZnO nanoparticles produced by Moringa (Alrabayah et al., 2022; Hamed et al., 2023; Kadhum et al., 2024).

Anticancer Activity of Moringa-Derived ZnO nanoparticles (ZnO NPs)

Mechanisms

It is mainly the formation of ROS, mitochondrial damage, DNA fragmentation, and stimulation of apoptosis that are the main anticancer effects of Moringa-derived ZnO NPs, and normal cells are usually spared. Such biogenic ZnO NPs are cytotoxic to many kinds of cancer cell lines, among them HeLa (cervical cancer), HepG2 (liver cancer), T47D (breast cancer), and A549 (lung cancer) (Table 4), with immunogenicity and activation of oxidative stress, mitochondrial dysfunction, DNA damage, p53, Bax/Bcl-2 imbalance, caspase activation, and cell cycle arrest at G2/M or S phase (Rafique et al., 2022; Shalaby et al., 2022). Phenolic or flavonoid-capped smaller nanoparticles (below 50 nm) are more likely to induce more apoptotic effects with lower doses than larger or uncoated nanoparticles (Anitha et al., 2021; Anjum et al., 2021; Mongy and Shalaby, 2024). ZnO nanoparticles prepared using Moringa oleifera leaf extracts exhibit ZnO NP dose-dependent cytotoxicity with an IC50 of around 26 to 210 µg/mL in various cancer cell lines (Shalaby et al., 2022). Also, ZnO/Ag hybrid nanoparticles prepared with Moringa had a stronger anticancer effect against HeLa cells than Ag or ZnO nanoparticles (Rafique et al., 2022). Table 4 summarizes key studies on Moringa-derived ZnO nanoparticles (ZnO NPs) and their anticancer effects:

Table No. 4: M. oleifera leaves, showing tested cancer cell lines, assays, and cytotoxicity outcomes.

NANOPARTICLE System / Plant Part	Cancer Cell Line(s)	Assays Used	Main Findings	Reference
ZnO/Ag NANOPARTICLES from Moringa leaves	HeLa (cervical cancer, ATCC CCL-2™)	Cell viability assay	Dose-dependent cytotoxicity: viability reduced to 60%, 50%, and 41% (24 h); 54%, 45%, and 35% (48 h); and 50%, 40%, and 31% (72 h) at 2.5, 5, and 10 µg/mL.	(Rafique et al., 2022)
ZnO nanoparticles (ZnO NPs) from Moringa leaves	T47D (breast cancer cells) HepG2 (liver carcinoma cells) A549 (lung carcinoma cells) Wi38 (normal fibroblasts)	Cytotoxicity assays (MTT)	IC_{50} = 38–210 µg/mL IC_{50} = 21–419 µg/mL IC_{50} = 26–115 µg/mL IC_{50} = 36–304 µg/mL	(Shalaby et al., 2022)

These findings support that Moringa-derived ZnO NPs are encouraging agents for targeted cancer therapy through ROS-dependent apoptosis and cell cycle modulation. Further research is required to maximize nanoparticle size and surface chemistry for maximal therapeutic efficacy with minimal side effects.

Biomedical Applications of Moringa-Derived ZnO nanoparticles (ZnO NPs)

Plant-mediated ZnO nanoparticles (especially from Moringa oleifera) show strong, size-dependent antimicrobial and emerging anticancer activity, mainly through ROS, membrane damage, and Zn^{2+} release.

Topical Antimicrobials and Wound Dressings

Plant-mediated ZnO nanoparticles are potentially effective against bacteria that are involved in wounds. including those resistant to multiple drugs such as S. aureus, P. aeruginosa, and E. coli. This efficacy is mainly due to the production of ROS, the liberation of Zn^{2+} ions, and the alteration of bacterial membranes (Asif et al., 2023; Al-Darwesh et al., 2024; Ali et al.,

2025; Mandal et al., 2022). These nanoparticles can be integrated into various forms, such as hydrogels, creams, films, and textile dressings, which provide sustained local antimicrobial effects and reduce the need for systemic antibiotics (Table 5) (Asif et al., 2023; Mandal et al., 2022; Ali et al., 2025; Shoukani et al., 2024). ZnO derived from medicinal plants (such as Moringa, Cycas, and Wodyetia) facilitates accelerated wound healing in animal studies, enhances fibroblast migration, and decreases oxidative stress and inflammatory markers, thus supporting their use in chronic, diabetic, and infected wounds (Ali et al., 2025; Alwadai et al., 2025; Moalwi et al., 2024; Elhabal et al., 2024).

Anticancer Nanomedicine and Drug Delivery

ZnO nanoparticles (ZnO NPs) are selectively toxic to cancer cells through the production of ROS, caspase-mediated apoptosis, mitochondrial damage, and tumor redox homeostasis disruption and have relatively lower cytotoxicity toward normal cells (Asif et al., 2023; Islam et al., 2022; Hussien et al., 2025; Alhujaily et al., 2022; Anjum et al., 2021). ZnO nanoparticles prepared by the use of polyphenol-rich extracts that are mediated by the plant can also increase the anticancer potency and offer inherent antioxidant/anti-inflammatory co-benefits (Al-Darwesh et al., 2024; Hussien et al., 2025; Alhujaily et al., 2022; Jan et al., 2021; Murali et al., 2021). ZnO nanoparticles (ZnO NPs) as responsive carriers to pH can be more rapidly dissolved in the acidic tumor microenvironment to deliver chemotherapeutics or plant bioactives to tumor tissue and minimize off-target toxicity (Islam et al., 2022; Murali et al., 2021; Anjum et al., 2021). Colloidal stability is enhanced by surface functionalization (i.e., theragnostic (therapy + imaging) nanoplatforms (Asif et al., 2023; Islam et al., 2022; Murali et al., 2021; Anjum et al., 2021).

Antifungal and Antibacterial Coatings

Plant-mediated ZnO nanoparticles (ZnO NPs) may be integrated into food packaging films, medical-device surfaces, and hospital contact points to stop the growth of bacteria and fungi and biofilm development (Asif et al., 2023; Hamed et al., 2023; Mandal et al., 2022; Alhujaily et al., 2022). These coating agents operate based on ROS production, cell wall disruption, and intracellular leakage and be active against Gram-positive, Gram-negative bacteria, and phytopathogen fungi (Hamed et al., 2023; Alhujaily et al., 2022; Alwadai et al., 2025; Moalwi et al., 2024). An example of using moringa or other vegetable-based ZnO nanoparticles (ZnO NPs) that are active against genera like Alternaria and Sclerotium demonstrates the opportunity of using these nanoparticles to create agricultural-protective coatings, which can be later applied to catheters and implants and high-risk clinical equipment to reduce healthcare-related infections (Figure 3) (Mandal et al., 2022; Alhujailly et al., 2022). Coating properties (thickness, porosity, adhesion, and controlled release of Zn^{2+}) should be optimized to achieve an optimal balance between the antimicrobial activity and cytocompatibility and lessen the leaching of nanoparticles (Asif et al., 2023; Mandal et al., 2022).

Antiviral Coatings and Formulations

Plant-mediated variants of ZnO nanoparticles (ZnO NPs) demonstrate antiviral effectiveness in vitro by damaging virions, initiating antiviral disarmament, and harming viruses through reactive oxygen species (Asif et al., 2023; Hussien et al., 2025; Jha et al., 2023). Studies reveal a significant level of inhibition against respiratory and enveloped viruses, which can be utilized in layers of masks, respirators, respirator filters, coatings for air filters, and films for high-contact surfaces (Asif et al., 2023; Jha et al., 2023). Additionally, plant-based ZnO systems may be considered for incorporation into antiviral topical sprays and gels; however, the current evidence is predominantly preclinical, and tests for toxicity and inhalation safety will be necessary before widespread use (Asif et al., 2023; Hussien et al., 2025; Jha et al., 2023).

Anti-inflammatory and Antioxidant Roles

Phytochemicals, which are not washed off the surface of ZnO NPs, are associated with additional biological properties, such as anti-inflammatory and antioxidant effects (Hussien et al., 2025; Jan et al., 2021; Al-Darwesh et al., 2024; Murali et al., 2021; Alhujaily et al., 2022). ZnO nanoparticles (ZnO NPs) synthesized by plant-based methods can be effective free radical scavengers and cytokine regulators, e.g., lowering IL-6, TNF-α, and IL-1β and increasing IL-10 in tissues in inflammation and diabetic wound models (Hussien et al., 2025; Alwadai et al., 2025; Jain and Bhise, 2025; Elhabal et al., 2024). Moreover, ZnO nanoparticles (ZnO NPs) not only offer protection against ultraviolet (UV) radiation and exhibit antioxidant properties but also have anti-acne potential when used in topical or cosmetic preparations. (Table 5). They are also more effective in biopolymer- or hyaluronic acid-based gels, which are more effective at improving skin hydration and fortifying the skin barrier for protection (Asif et al., 2023; Crainic et al., 2025; Murali et al., 2021). Nevertheless, the anti-inflammatory and antioxidant activity of these NPs depends on the dose. Overexposure either locally or systemically could lead to oxidative stress and organ toxicity. Thus, to make nanoparticles (Hamed et al., 2023; Jiang et al., 2018).

Biomedical Implication

Comprehensively, moringa leaves are the most favored part of the plant that can be utilized as a source of ZnO to be used against microbes. antioxidant biomedical applications, because of their abundant phenolic nature and wide application in ZnO studies using plants in research (El-Saadony et al., 2024; Murali et al., 2021; Okaiyeto et al., 2024). Others tried include seeds, roots, flowers, and gums, and future studies will need to optimize specific applications of these nanoparticles to wound care,

infection control, and antioxidant treatment, but comparative data on specific Moringa-based nanoparticles remain limited (Murali et al., 2021; Tao et al., 2025; Okaiyeto et al., 2024).

Table 5. Comparative table outlining diverse biomedical and applied uses of plant-driven ZnO NPs, highlighting antifungal, antibacterial, antiviral, antioxidant, and broader therapeutic potentials

Category	Main material/source	Key mechanism	Main biomedical use	references
Topical antimicrobials/wound	Moringa root–mediated ZnO, PEG-coated, ciprofloxacin-loaded NANOPARTICLES	ROS generation, membrane disruption, and controlled ciprofloxacin release	Topical nano-drug carrier for skin infections and wound healing	(Shoukani et al., 2024)
	Moringa leaf–ZnO NPs (green synthesized)	Broad-spectrum antibacterial + strong antioxidant activity from ZnO + Moringa phytochemicals	Potential gels/creams for C. acnes, S. aureus, E. coli, and antioxidant skin protection	(Bhalla et al., 2022; Sarwar et al., 2025)
	Moringa gum–ZnO NPs)	ROS, membrane damage; strong activity vs. MRSA	Antibacterial agent for multidrug-resistant wound pathogens	(Irfan et al., 2021)
Anticancer nanomedicine/drug delivery	Plant-mediated ZnO NPs (incl. Moringa systems in broader review)	ROS-mediated DNA/mitochondrial damage, Zn^{2+} release, apoptosis; pH-responsive release	Emerging anticancer nanocarrier for selective tumor toxicity	(Murali et al., 2021; Hamed et al., 2023; Hussien et al., 2025)
Anticancer/cytotoxicity (Moringa-extract nanoparticles panel)	Moringa leaf–ZnO among multiple metal nanoparticles	ROS-linked, size-dependent cytotoxicity; time- and dose-dependent effects	In vitro anticancer activity (e.g., T47D, A549) at sub-millimolar doses	(Shalaby et al., 2022)
Antifungal & antibacterial coatings	Moringa peel–ZnO NPs	ROS, membrane damage, and strong activity vs. Alternaria, Sclerotium, and bacteria	Antifungal/antibacterial coatings for agriculture, textiles, and possibly medical surfaces	(Surendra et al., 2016)
	Moringa seed–ZnO NPs)	ROS + surface interaction, broad microbicidal effect	Antimicrobial coatings with additional photocatalytic/adsorptive functions	(Kalaiyarasi et al., 2022)
Antiviral coatings/formulations	Plant-mediated ZnO NPs)	ROS, lipid envelope, and RNA damage, surface contact killing	Surface/filter coatings for viral inactivation (HSV-1, coronaviruses; conceptually extendable to Moringa-ZnO)	(Hamed et al., 2023; Murali et al., 2021)
Anti-inflammatory & antioxidant	Moringa leaf–ZnO NPs)	Free-radical scavenging by ZnO plus Moringa polyphenols	Anti-inflammatory and antioxidant support in dermal / wellness products	(Bhalla et al., 2022; Murali et al., 2021; Sarwar et al., 2025)

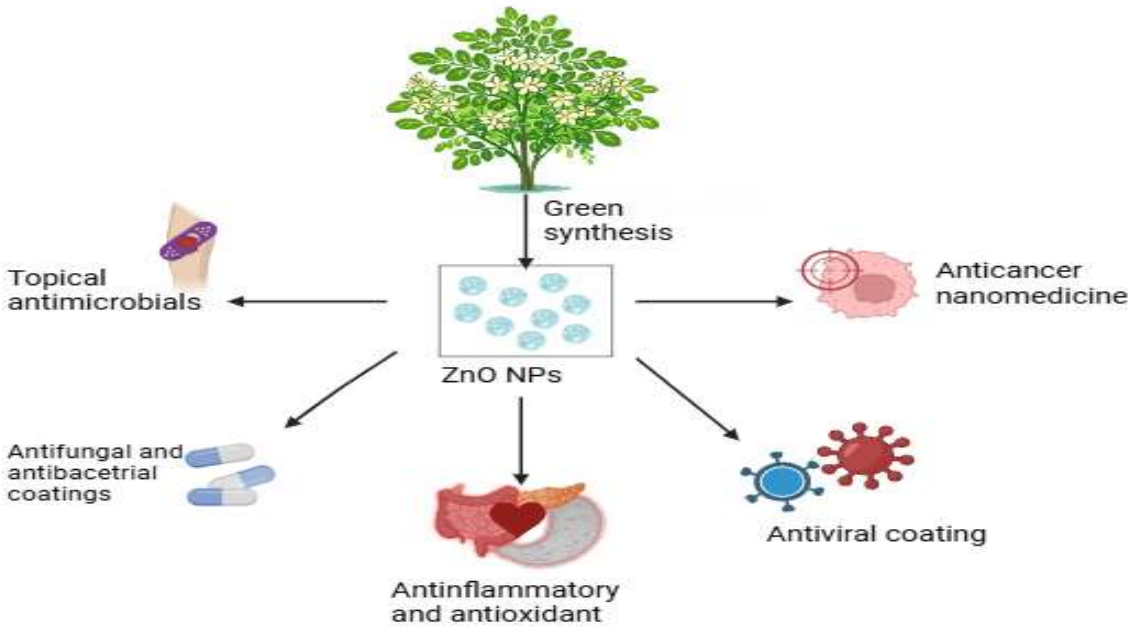

Figure 3: Diagram summarizing multifunctional biomedical applications of Moringa-derived ZnO NPs

Toxicological Considerations in Organically made ZnO NPs of Moringa

Moringa oleifera leaf-extract-synthesized ZnO nanoparticles exhibit enhanced antimicrobial and anticancer properties and generally superior biocompatibility compared with chemically produced ZnO; however, their safety is reliant upon factors such as dosage, particle size, and the specific application context (Hamed et al., 2023; El-Beltagi et al., 2024; Mandal et al., 2022; Sarwar et al., 2025).

Cytotoxicity to Normal Cells

Green-mediated ZnO NPs show significant antimicrobial and antioxidant activity mediated by Moringa phytochemicals that act as reducing agents and caps and may improve stability and biocompatibility (Bhalla et al., 2022; El-Beltagi et al., 2024; Matinise et al., 2017; Sarwar et al., 2025). In contrast, ZnO NP cytotoxicity depends on dose and size during exposure to malignant and normal mammalian cells: increased dosage with smaller particles is more toxic via membrane damage and intracellular mechanisms (Hamed et al., 2023; Mandal et al., 2022; Perumalsamy et al., 2024; Shalaby et al., 2022). While phytochemical caps of plant-mediated ZnO NPs may limit direct contact with cellular membranes, there has not been extensive testing on normal human cell lines and in vivo models (Hamed et al., 2023; Mandal et al., 2022).

Oxidative Stress and Cellular Damage

The production of ROS underlies oxidative stress. While this process is vital for antimicrobial and anticancer mechanisms, it can also harm DNA, lipids, and proteins (Hamed et al., 2023; Perumalsamy et al., 2024; Mandal et al., 2022). Excessive ROS can trigger necrosis or apoptosis. Cells treated with ZnO NPs have shown mitochondrial damage and genotoxic effects (Hamed et al., 2023; Perumalsamy et al., 2024). Due to co-delivered phytochemicals that may mitigate oxidative damage at appropriate concentrations, ZnO nanoparticles synthesized from Moringa exhibit significant antioxidant and radical-scavenging properties (Bhalla et al., 2022; Sarwar et al., 2025).

Biodistribution, Environmental Impact, and Dose Limits

ZnO NPs can pile up in the liver, kidney, and other tissues/organs before degradation into Zn^{2+}; high levels of bioaccumulation can be harmful, contradicting low-dose safety expectations (Fujihara & Nishimoto, 2023; Hamed et al., 2023; Mandal et al., 2022). While using plants as reducing agents helps prevent chemical remnants on nanoparticles, excessive use and environmental discharge can harm microbial populations and surrounding organisms via oxidative stress (Fais et al., 2024; Hamed et al., 2023; Mandal et al., 2022). Toxicity relies on particle size, amounts, and exposure duration, and many different doses have been deemed toxic. No definitive safe dose has been described for ZnO NPs produced from Moringa (El-Beltagi et al., 2024; Hamed et al., 2023; Mandal et al., 2022; Perumalsamy et al., 2024; Shalaby et al., 2022).

Research gap

The antimicrobial and anticancer activity of Moringa-mediated ZnO NPs has been confirmed as positive in the studies, and this is primarily explained by the high levels of phytochemical composition of the plant that can become reducing and capping agents during the synthesis (Perumalsamy et al., 2024; Sarwar et al., 2025; Shashikala et al., 2024). However, the complete comprehension of the functioning governing these bioactivities and the effect of these morphological and surface chemistry changes among constituents of the Moringa plant, or production state, on the therapeutic

efficacy and selectivity of the processes remains a significant knowledge gap (Perumalsamy et al., 2024; Matinise et al., 2017). The direct comparison of specific Moringa extracts (leaves, seeds, gum, roots) with standardized ZnO nanoparticle properties and their further biological behaviors is not carried out, which does not allow optimization to be utilized in clinical practice (Abel et al., 2021). In vitro antimalarial and anticancer properties were also reported, but no complex studies and toxicity tests were done to show the safety and efficacy in living organisms (Shalaby et al., 2022; Sarwar et al., 2025). The potential synergistic effects of the doping of ZnO nanoparticles (ZnO NPs) with other metals synthesized with the assistance of Moringa extracts (e.g., silver) should also be investigated to improve the bioactivity (Venkatraman et al., 2024; Rafique et al., 2022). These gaps will be significant in addressing the gaps between the laboratory studies of the Moringa-mediated ZnO NPs and the real biomedical use.

Conclusion

The green synthesis of zinc oxide nanoparticles (ZnO NPs) using *Moringa oleifera* has emerged as a promising and sustainable approach within the field of nanobiotechnology. Moringa oleifera leaf extract, such as flavonoids, phenolic acids, proteins, tannins, and more, contains numerous bioactive agents that aid in the reduction, stabilization, and capping processes during the biosynthesis of nanoparticles. Green nanoparticles have been shown to have higher biological activity. The nanoparticles formed when using ZnO have been shown to range from ~10–60 nm and display spherical morphology, but can also possess a hexagonal wurtzite formation. Zinc oxide nanoparticles synthesized from Moringa oleifera extracts have shown antibacterial, antifungal, and anticancer activity against numerous microbes and cell lines, respectively. This activity is said to occur through ROS generation, membrane disruption, Zn^{2+} release, and disturbance in cellular metabolism, among other mechanisms. Zinc oxide nanoparticles produced using various parts of the Moringa plant (including the leaves, seeds, flowers, roots, and gum from bark) have exhibited promising biomedical applications due to these capabilities. Potential applications include the use of ZnO nanoparticles as antimicrobial agents in coatings, wound dressings, drug delivery vehicles, and even as anticancer agents. While studies have been conducted in this field, many are only in vitro and in vivo studies; toxicity analysis and clinical trials need to be conducted. There needs to be more consistency between studies using plant extracts because there can be variations in the phytochemical makeup of the extracts used, synthesis methods, and nanoparticle characterization.

In addition, direct antiviral investigations involving *Moringa*-mediated ZnO nanoparticles are limited, representing a research gap and a potential direction for future experiments. Expanding research into antiviral applications, along with evaluating biocompatibility, environmental safety, and large-scale production feasibility, will be crucial for translating these materials into practical biomedical and industrial applications.

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Statements and Declarations

Data Availability statement

All relevant data are within the manuscript file.

Author's Contribution Statement

MA, MS, and SY conceived the study, collected and analyzed data, wrote the manuscript. DA supervised, provided resources. MA and SHUHS critically reviewed, edited, and provided resources. All authors have read the final manuscript and approve its submission.

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No conflict of interest.