Article

Biogenic Nanoparticles and Green Nanocomposites as Sustainable Antimicrobial Strategies Against Bacteria, Fungi and Viruses

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Abstract

The field of nanotechnology, specifically the manipulation of materials at the nanoscale (1–100 nm), has gained significant attention owing to its diverse applications in biotechnology, nanomedicine and environmental sustainability. While nanoparticles synthesised using green methods such as plants, fungi and bacteria offer eco-friendly alternatives to conventional nanoparticles, green composite nanomaterials, which integrate biogenic nanoparticles with natural polymers or fibres, provide enhanced stability, controlled release and multifunctional antimicrobial properties. For instance, silver nanoparticle–chitosan composites have been successfully applied in wound dressings and food packaging, demonstrating real-world applications. These green composites exhibit antimicrobial activity through mechanisms including reactive oxygen species generation, membrane disruption, ion release and biofilm inhibition. This review discusses methods for synthesising both green nanoparticles and composites, their antimicrobial efficacy against bacteria, fungi and viruses, and practical applications in the medical, agricultural and environmental sectors. Challenges related to toxicity, scalability and environmental impact are also highlighted. Overall, green composite nanomaterials represent a sustainable and effective strategy for combating microbial resistance and promoting global health.

Keywords: nanoparticles; nanocomposites; antimicrobial resistance; nanomedicine; sustainable materials

1 Introduction

Nanotechnology has revolutionised numerous industries by providing innovative solutions in fields such as medicine, environmental science, and catalysis. Green composite nanomaterials, which are created by combining nanoparticles (NPs) with sustainable materials, focus on the manipulation and regulation of substances at the nanoscale (1 to 100 nm) [1]–[4]. These materials have shown significant potential in applications across medicine, electronics, energy production and consumer goods [5], [6]. The properties of these NPs, such as size, shape and stability, are influenced by various factors, including pH, temperature, growth media, synthesis conditions and surface characteristics [7], [8]. Green composite nanomaterials not only exhibit antimicrobial properties but are also produced via eco-friendly synthesis routes that minimise chemical hazards and energy consumption. These sustainable approaches enhance their applicability in sectors such as healthcare and environmental management, where the demand for biodegradable, non-toxic and effective antimicrobial materials is high. Green composite nanomaterials, with their antimicrobial properties, have garnered attention in sectors such as nanomedicine, pharmaceuticals, agriculture, environmental science and targeted drug delivery owing to their ability to combat pathogenic bacteria, fungi and viruses [9]–[12]. The antimicrobial activity of these green composites is influenced by factors such as NP size, synthesis conditions and the properties of the biomaterial used [13], [14]. By integrating green synthesis approaches with practical applications, such as biodegradable wound dressings, antimicrobial food packaging and water purification systems, these materials demonstrate a direct link between sustainability and functional utility. This emphasises the dual benefit of using eco-friendly methods to produce materials that address both environmental and healthcare challenges.

Green synthesis methods offer advantages such as cost-effectiveness, sustainability and environmental safety, which make them a promising alternative to traditional methods [15]. These nanomaterials have demonstrated potential in applications such as photocatalysis, electrochemical sensing and biofilm control, while being less harmful to humans and the environment [16], [17]. There are three primary methods via which NPs can be produced, namely, physical, chemical and biological processes. Chemical methods are widely used but offer limited advantages. Their major drawback is that they are not environmentally friendly methods of synthesis. While physical methods exhibit potential with regard to environmental sustainability, biological methods respond to the principles of green chemistry to a much greater extent [18]. Physicochemical properties of NPs differ substantially from those exhibited by larger particles. The optical, mechanical, chemical, magnetic and electrical properties of these materials show their distinct characteristics and potential applications, and also exhibit distinct microbial activity, such as antibacterial or antiviral [19], [20].

The demand for fibre-reinforced polymer composites has increased significantly in the commercial industry in recent years. The reinforced polymer composite provides various benefits, such as preserving limited supplies of traditional resources [21]. Nevertheless, proper removal of this type of composite material is a significant concern because of the non-biodegradable properties of the petroleum-based polymer and synthetic fibre. Engineers have directed their attention to the environmental issue by focusing on the sustainability of materials and transitioning towards the advancement of biomaterials. The first biomaterial, consisting of cotton fibre and either phenol, was produced in 1908 [22]. Not all biomaterials are completely biodegradable until the constituent materials are produced from renewable sources. Significant research has been conducted on the development of a completely degradable and environmentally friendly biomaterial known as green composites.

Biodegradable polymer and natural lignocellulosic bio-fibre make up these materials. Living organisms may break down these compounds into water and carbon dioxide through enzymatic action. Indoor products with a beneficial life of several years and outdoor consumer products with a one- to two-year lifecycle can be produced from green composites [23]. Green composites have grown in their use in engineering by replacing synthetic fibre-reinforced components. Green composites have gained interest in education and industry because of their advantages, including low density, high strength, recyclability, profitability and environmentally friendly practices. A range of natural and synthetic biodegradable materials can be used for green composites [24].

Composites are commonly used owing to their many applications and capacity for combining with other materials for specific uses and desired characteristics. Composites such as metal matrix, nano, fibre reinforced, and hybrid have become prevalent throughout several sectors. Our current focus is on creating eco-friendly green composites. Green composites, a type of biocomposite, are a new field in polymer science that combines a bio-based polymer matrix with natural fibres. Green composites fabricated from biodegradable, renewable materials have gained interest owing to environmental issues regarding conventional plastics and the global need for fossil resource alternatives [25], [26].

This review focuses on the biological synthesis of both green nanocomposites (NCs) and individual biogenic NPs using plant materials, bacteria, fungi and algae, with a particular emphasis on their antimicrobial properties. It distinguishes between single NPs and composite materials, exploring how the integration of NPs with natural polymers or fibres enhances their antibacterial, antifungal and antiviral activities. The novelty of this review lies in its clear differentiation of biogenic NPs from true composite nanomaterials and its focus on how eco-friendly synthesis approaches contribute to sustainable, practical applications in medicine and environmental protection. This work demonstrates the real-world utility of both green NCs and individual biogenic NPs in addressing global health and environmental challenges.

2 Search Strategy, Screening Flow and Quality Appraisal

To ensure the quality and comprehensiveness of the studies included in this review, a transparent search strategy was implemented following PRISMA guidelines. A thorough literature search was conducted across major databases such as PubMed, Google Scholar, ScienceDirect and Web of Science using keywords related to “green synthesised nanoparticles”, “green composite nanomaterials”, “antimicrobial activity”, “nanotechnology” and “nanocomposites” with the inclusion of studies published between 2008 and 2025. Inclusion criteria focused on studies employing standard antimicrobial assays such as MIC and zone-of-inhibition protocols. In addition, a bias risk assessment was performed to ensure the inclusion of studies with reproducible and reliable results, maintaining high methodological standards throughout the review process.

3 Overview of Green Nanocomposites and Biogenic Nanoparticles

Green composite nanomaterials are NCs that are produced by using eco-friendly and sustainable materials and methods. These materials are specifically engineered to minimise their environmental impact in comparison to traditional composites, which commonly rely on non-renewable resources and energy-intensive manufacturing techniques [27]–[29]. By using various species as stable and environmentally safe precursors, biological synthesis can produce durable and bio-functional NPs. Reports have indicated the utilisation of biomass filtrate obtained from various biological systems, such as yeast, actinomycetes, plant extract, fungus, algae and bacteria, for the greener synthesis of NPs [30]. Green composite nanomaterials synthesised through biological methods have shown great promise in a variety of biomedical applications. Plant extracts, bacteria, fungi and algae play key roles in the green synthesis of NPs, offering an eco-friendly and sustainable approach [7]. Plant-mediated synthesis utilises the reducing and stabilising properties of plant metabolites, such as polyphenols and alkaloids, to produce NPs with unique biological activity [31]. Biogenic NPs are an emerging class of materials synthesised through biological processes involving plants, fungi, bacteria and algae.

These NPs offer a sustainable alternative to traditional chemical synthesis methods, as they are derived from renewable, environmentally friendly sources [3], [15]. Biogenic NPs, including silver (Ag), copper (Cu), and zinc oxide (ZnO), have shown significant antimicrobial, antifungal and anticancer properties [8], [32]. Their synthesis often involves the reduction of metal ions using plant metabolites, enzymes or fungal/bacterial cell walls [33]. The unique biological properties imparted by these NPs enhance their effectiveness in various applications, including biomedical fields such as drug delivery, wound healing, and diagnostics. Biogenic NPs are particularly notable for their ability to combat drug-resistant pathogens and promote tissue regeneration, offering a promising pathway for overcoming challenges in medical treatment [34]. Similarly, bacteria and fungi, through their metabolic pathways, are capable of synthesising NPs that exhibit antimicrobial, antifungal and anticancer properties [35]. Algae-based synthesis, with its unique combination of bioactive compounds, also contributes significantly to the production of NPs with applications in drug delivery and wound healing [36]. These biological systems not only provide a green alternative to chemical synthesis but also enhance the functional properties of nanomaterials, making them more suitable for biomedical use. The incorporation of these naturally derived NPs into biomedical devices, such as wound dressings, drug carriers and diagnostic tools, is expected to revolutionise the field by offering safer, more effective and environmentally friendly solutions.

Studies have demonstrated the increased efficacy of these biogenic NPs, especially in combating drug-resistant microorganisms and promoting tissue regeneration, showing their immense potential for future medical applications [34]. Figure 1 illustrates the synthesis of NPs and NCs using biological sources and their diverse applications. The left side of the figure shows the biological sources, including bacteria, plants, fungi and algae, which act as green sources for NP synthesis. The synthesis process involves biological reduction and stabilisation with the help of secondary metabolites and biosurfactants, leading to the formation of capped NPs. On the right side, the figure highlights various applications of these green composite nanomaterials, including enzyme immobilisation, cosmetic formulations, drug delivery, antimicrobial activity, biosensors, blood compatibility, cancer treatment, wound healing, diagnostics and gene therapy. While biological synthesis offers eco-friendly and sustainable alternatives, scaling up these processes for industrial production requires optimisation of biomass supply, reaction conditions, and downstream processing. Although green synthesis may have higher initial costs than conventional chemical methods, it reduces hazardous waste, energy consumption and environmental impact, which makes it a more sustainable option for large-scale applications. These materials are revolutionising drug delivery systems, providing targeted treatments while minimising side effects. In addition, their antimicrobial properties are being leveraged to combat infections, while their use in diagnostics enhances disease detection. Nanomaterials are also advancing wound healing, cancer treatment and gene therapy, showing immense potential for improving human health through innovative, environmentally conscious solutions.

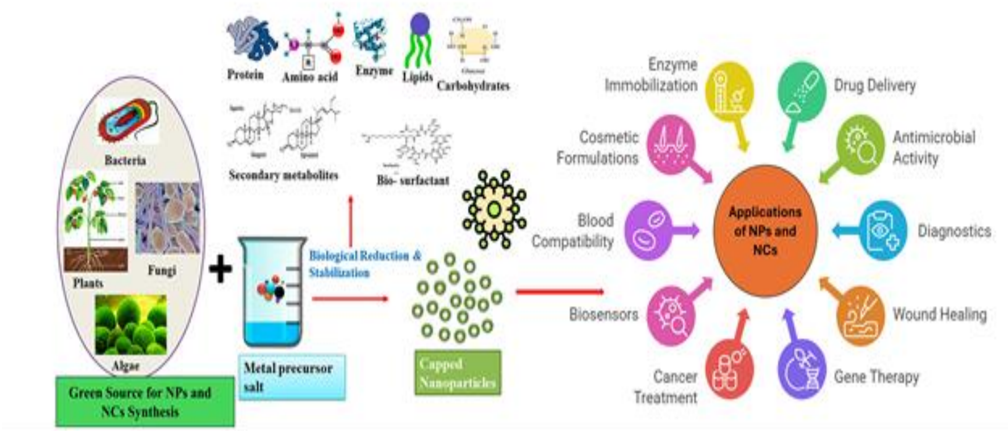

Figure 1: Green NCs and biogenic NPs: Synthesis, capping agents, and applications

4 The Antimicrobial Potency of Green Nanocomposites and Biogenic Nanoparticles

Antimicrobial green composite nanomaterials exhibit the combined advantages of environmentally friendly and sustainable materials, together with antimicrobial properties. These materials are used in many sectors such as healthcare, food packaging and environmental protection. For example, silver–chitosan composites have been successfully employed in wound dressings to prevent infections, and zinc oxide–polymer composites are applied in antimicrobial food packaging to extend shelf life and reduce microbial contamination. Antimicrobial green composite NPs offer a novel and eco-friendly solution to combat microbial contamination in many applications, while reducing the environmental problems related to conventional antimicrobial materials [37], [38]. Microbial resistance is a major medical issue, and improvements in green synthesis keep researchers interested in its pathogenic microbe-fighting potential. Silver, copper, gold, zinc and other bioinspired metal NPs inhibit Gram-positive and Gram-negative bacteria and pathogenic fungi such as *A. niger*, *F. oxysporum* and *A. fumigatus*. Green synthesised NPs can result in excess reactive oxygen species (ROS) in microbes, damage microbial plasma membranes, cause accumulation of metal ions in membranes, disrupt metabolic activities through electrostatic interactions, and inhibit microbial proteins/enzymes by increasing H_2O_2 production.

The antimicrobial mechanisms of green composite nanomaterials differ depending on the type of pathogen. For bacteria, ROS generation, membrane disruption, ion accumulation, and enzyme inhibition dominate, which lead to cell lysis and metabolic disruption. For fungi, inhibition of spore germination, disruption of hyphal membranes, and biofilm degradation are key mechanisms. For viruses, NPs can block viral attachment to host cells, prevent viral entry, and inhibit replication, which reduce infectivity. These mechanisms are directly linked to practical applications. In clinical settings, silver–chitosan composites in wound dressings prevent bacterial infections and promote healing. In the food industry, zinc oxide–polymer composites reduce microbial contamination and extend shelf life. In environmental applications, NP-infused water filtration systems inhibit microbial growth, ensuring safer water supplies.[39]. Biogenic NPs, synthesised through biological processes using plant extracts, fungi, bacteria and algae, offer an eco-friendly and sustainable alternative to traditional chemical methods. These NPs, including silver (Ag), copper (Cu), zinc oxide (ZnO), gold (Au), iron oxide (Fe_3O_4), selenium (Se), and titanium dioxide (TiO_2), are especially renowned for their antimicrobial potency [40]. Silver NPs are widely studied for their potent antibacterial, antifungal and antiviral properties [41], while copper and zinc oxide NPs exhibit strong antimicrobial effects against a wide range of bacteria and fungi [42]. Iron oxide and selenium NPs also show significant antimicrobial activity, with selenium NPs demonstrating additional antioxidant properties [43], [44].

The unique antimicrobial mechanisms of these biogenic NPs, such as ROS generation, membrane disruption and ion release, make them highly effective in combating drug-resistant pathogens, promoting their use in medical, agricultural and environmental applications [34]. Antibacterial bio-NCs used in biological fields can be categorised according to the specific material used, which possesses antibacterial properties. Furthermore, Tables 1 and 2 present a comprehensive summary of several studies on the antibacterial properties of bio-NC nanomaterials and their practical applications. Figure 2 shows an evidence map of antimicrobial mechanisms of NPs and NCs. It highlights ROS generation, ion release, membrane damage, biofilm disruption and viral attachment inhibition. These mechanisms demonstrate how NPs and NCs disrupt microbial and viral activity through oxidative stress, ion interaction, membrane destabilisation, biofilm interference, and blocking viral entry.

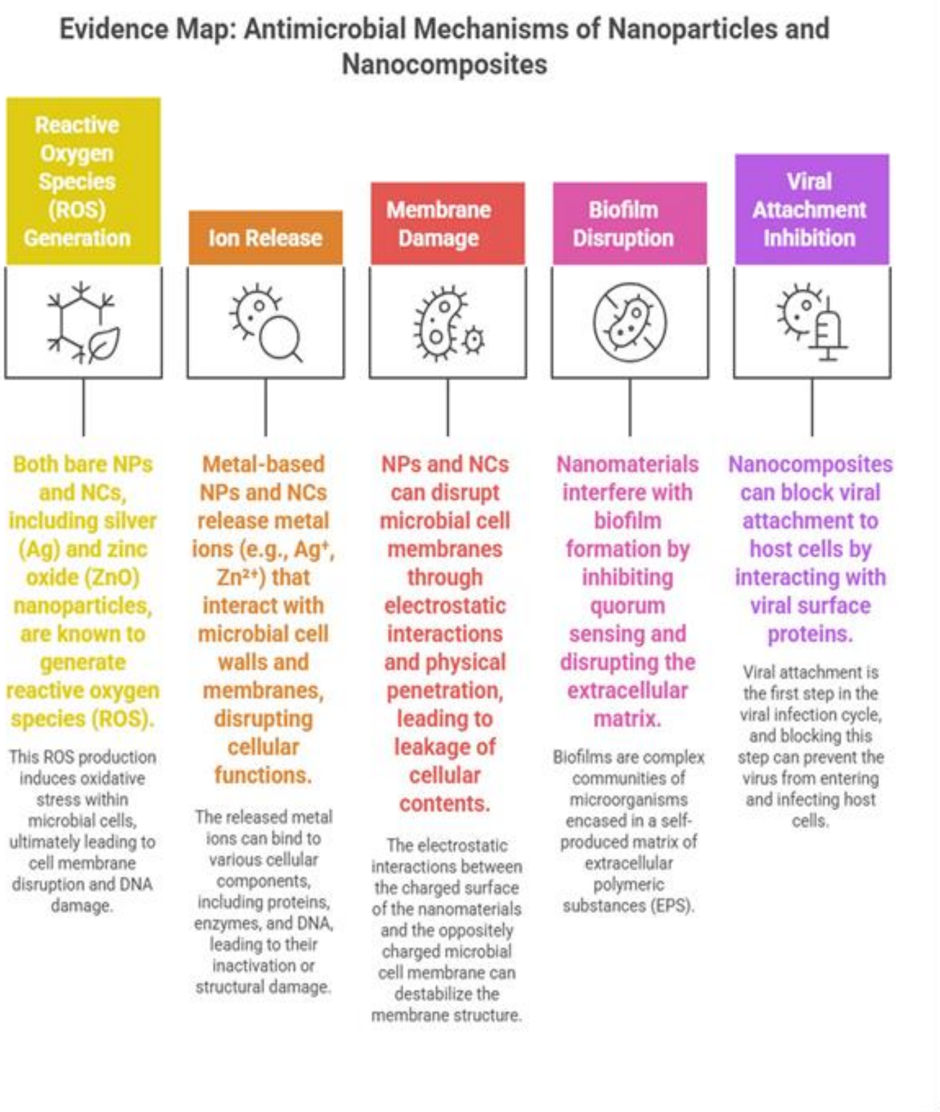

Figure 2: Antimicrobial and antiviral mechanisms of NPs and NCs: ROS generation, ion release, membrane damage, biofilm disruption and viral attachment inhibition

Table 1: Antimicrobial potential of green composite nanomaterials and biogenic nanoparticles from biological sources

Nanoparticles/composites	Biological source	Applications	References
Chitosan/Fe_2O_3/ZnO NC	Chitosan (biopolymer) + Fe_2O_3 (metal oxide) + ZnO (metal oxide)	Antibacterial: *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, antifungal: *Candida albicans*, anti-biofilm, antioxidant, wound healing, cytotoxicity (tested on WI-38 cells)	[45]
Cannabis sativa fibre reinforced granite filler epoxy matrix composite	*Cannabis sativa* (fibre) + granite (mineral)	The composite exhibited antibacterial activity against *E. coli*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Candida albicans*	[46]
$CuSO_4$ and CuO in cellulose acetate (CA) fibres	Copper (Cu) + CA	Antiviral: $CuSO_4$ demonstrated high efficacy against SARS-CoV-2 (IC50 0.45 mg/L) and Influenza A (IC50 1.395 mg/L). Antibacterial: Inactivated *E. coli* and *S. aureus*	[47]
ZnO, ZnO–Ag, ZnO–Cu NCs	*Bridelia ferruginea* (dye)	Antimicrobial potential (due to phytochemicals in dye)	[48]
Ag, Cu, TiO_2 NPs	*Artemisia haussknechtii* (leaf)	Effective against MDR *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Serratia marcescens* and *Escherichia coli*	[49]
CuONPs	*Piper nigrum* (fruit extract)	Antibacterial activity against *Escherichia coli* (larger inhibition zone) and *Staphylococcus aureus*, with NP size up to 60 nm	[50]
CuO-Ag NPs	*Withania coagulans* (extract)	Exhibited significant antibacterial activity against *E. coli* (20.67 mm zone) and *P. aeruginosa* (19.00 mm zone)	[51]
Ag/Cu NCs	*Sargassum latifolium* (marine algae)	Exhibited antibacterial activity against *B. subtilis* (38.0 mm) and *S. epidermidis* (25.0 mm)	[52]
Cur-Ag NPs and Cur-ZnO NPs	Curcumin extract	Cur-Ag NPs exhibited strong antimicrobial activity against most bacterial isolates except *Proteus vulgaris*; Cur-ZnO NPs exhibited activity against all tested strains	[53]

Nanoparticles/composites	Biological source	Applications	References
Ag, Cu, Au, ZnO, MgO, Co_3O_4, TiO_2 NPs	Plant extracts (leaves, barks, roots, etc)	Effective against bacteria, fungi and viruses by disrupting microbial membranes, generating ROS, and interfering with DNA and protein synthesis	[54]
Ag@ZnO–CeO_2 nanostructures (NS)	*Moringa oleifera* (leaf extract)	Removal of ciprofloxacin antibiotic (74%) and methylene orange dye (85%) from wastewater under sunlight	[55]
Ag-doped SnO_2 NPs	Plant extract	Significant antimicrobial activity against *Staphylococcus aureus* (29 mm), *Escherichia coli* (27 mm), *Fusarium oxysporum* (17 mm), and *Fusarium graminearum* (15 mm)	[56]
Ag NPs/LDH-*Matricaria chamomilla* NC	Ag NPs/LDH-*Matricaria chamomilla* NC	Effective against Gram-positive (*Staphylococcus aureus*, *Staphylococcus epidermidis*) and Gram-negative (*Escherichia coli*, *Pseudomonas aeruginosa*) bacteria	[57]
AgNPs	*Salvia officinalis* (leaf extract)	Significant activity against multidrug-resistant bacteria, with the highest inhibitory zone (37.86 mm) against *Escherichia coli*; Synergistic effect with colistin against *Acinetobacter baumannii* (85.57% synergistic activity)	[58]
Ag and Ce Dual-Doped ZnO NP	Taranjabin (natural resin)	Antibacterial and antifungal properties	[59]
Ag, Au, Co, Cu, Fe, Zn, Ti, Mg, Pd, Pt, Ni, Zr, Bi_2O_3, CeO_2, Co_3O_4, CuO, Fe_2O_3, MgO, NiO, TiO_2, ZnO, ZrO_2	Plants (Phytoconstituents such as polyphenols, flavonoids, terpenoids, glycosides, alkaloids)	Antibacterial, anticancer, antiviral, and biofilm inhibitory activities	[60]
Ag/CaO NCs	*Zingiber officinale* (ginger extract)	Strong activity against *E. coli* and *S. aureus*. Inhibited dihydrofolate reductase, DNA gyrase, and FabB enzymes	[61]
Mono-substituted HAp with Ag^+, Ce^{3+}, Cu^{2+}, Ga^{3+} and Mn^{2+}	Hydroxyapatite (HAp)	Ag-substituted HAp showed significant activity against *E. coli*, *S. aureus*, *A. baumannii*, *K. pneumoniae*, and *P.*	[62]

Nanoparticles/composites	Biological source	Applications	References
		aeruginosa. Ce-substituted HAp showed no activity. Ga- and Mn-substituted HAp exhibited some antibacterial potential	

Table 2: Selected studies reporting the antimicrobial potential of green composite nanomaterials and biogenic nanoparticles against different pathogenic microbes

Target microorganisms	NP type, size (nm)	Biological agent used for synthesis/ biological entity	Antimicrobial activity method	References
E. coli, *P. aeruginosa*, *K. pneumoniae*, and *S. aureus* (bacteria) *A. niger* and *C. albicans* (fungi)	CuO/C NCs, 7–11	*Adhatoda vasica*	Agar well diffusion method	[63]
B. cereus, *S. aureus* (ATCC 6538), *Enterococcus hirae* (ATCC 10541), *E. coli* (ATCC 10536), *P. aeruginosa* (ATCC 9027), *Legionella pneumophila* subsp. *pneumophila* (ATCC 33152), and *C. albicans*	Palladium NPs, 7.44 to 1.94	*Urtica dioica*	Micro-dilution method	[64]
E. coli, *P. aeruginosa*, *Salmonella typhimurium*, *Klebsiella pneumoniae*, and *Proteus vulgaris* (Gram-negative Bacteria); *B. subtilis* and *S. aureus* (Gram-positive Bacteria); *C. albicans* and *A. parasiticus* (fungi)	Bacterial cellulose/Nano bioactive glass, between 14 and 30	In situ fermentation with NBG; BC-producing strain *Gluconacetobacterxylinus*	Agar well diffusion procedure	[65]
E. coli - MNCL2832, *S. typhimurium* - MNCL2501, *P. aeruginosa* MNCL5032 (Gram -ve bacteria); *B. cereus* -MNCL2703 (Gram +ve bacterium); *A. niger* -NCIM1207, *Fusarium solani* -	AgNPs decorated ZnO NCs, AgNPs: 1.1 to 1.5 ZnO: 0.3 to 0.4	Gongura leaves for AgNPs	Agar well diffusion method	[66], [67]

Target microorganisms	**NP type, size (nm)**	**Biological agent used for synthesis/ biological entity**	**Antimicrobial activity method**	**References**
JALPK (fungi)				
E. coli, *S. aureus*, *P. aeruginosa* and *C. albicans*	AgNPs, 1.2 to 62 (avg. 5)	*Lysiloma acapulcensis*	Disk diffusion method	[68]
B. subtilis (Gram +ve), *E. coli* (Gram -ve)	Cu NPs, 5–20	*Curcuma longa*	Agar well diffusion method	[69]
P. aeruginosa, *B. subtilis* and *S. aureus*	2.8	Orange waste (peels)	Not specified in the given extract	[70]
S. aureus, *E. coli*, *Listeria monocytogenes*, *A. favus*, and *Penicillium spinulosum*	FeO-NP, 8.03	Aqueous extract of *Laurus nobilis* L. leaves	Disk diffusion method	[63]
Microorganisms (*S. aureus* CCM 4223, *L. monocytogenes* CCM 4699, *E. coli* CCM 3988, *Serovar typhimurium* CCM 7205 and *P. aeruginosa* CCM 3989)	AgNPs, 46.1 (OV-AgNPs), 37.8 (LA-AgNPs), 14.7 (BN-AgNPs), 16.2 (CBP-AgNPs), 75.7 (BV-AgNPs)	*Berberis vulgaris*, *Brassica nigra*, *Capsella bursa-pastoris*, *Lavandula angustifolia*, *Origanum vulgare*	Agar method (details not fully specified)	[71]
P. otitidis (MCC 2509), *P. oleovorans* (MCC 2566), *Acinetobacter baumannii* (MCC 2366), *B. cereus* (MCC, 2039), and *Enterococcus faecalis* (MCC, 2041)	ZnO NPs, 50	*Pseudomonas putida* (MCC 2989) broth culture	Agar well diffusion assay, Congo red agar method (CRA)	[72]
H1N1 virus	GF-Au NPs, 32	*Glaucium flavum* leaf extract	Reed and Muench formula method	[73]
Coronavirus 229E	ZnO NPs, 6.80	Maesa indica Roxb. Sweet (ME) aerial parts	Cytotoxicity assay	[74]
Hepatitis A virus (HAV) and Coxsackie B virus (Cox-B4)	Se-NP, 2–22	*Portulaca oleracea*	MTT assay	[75]
Laryngotracheitis virus and bronchitis virus	ZnO NPs, 71–214	*Prunus dulcis* extract	In vitro infection experiment combined with immunofluorescence	[75], [76]

Target microorganisms	NP type, size (nm)	Biological agent used for synthesis/ biological entity	Antimicrobial activity method	References
			staining of the infected cells	
H3N2 (A/H3N2), feline calicivirus (FCV) viruses	Poly (tannic acid)-based silver NCs, 10.61	Tannic acid	Tissue culture infectious dose 50% method	[77]

4.1 Mechanism of Antimicrobial Activity of Nanocomposites and Nanomaterials

Metal NPs interact significantly depending on the metal and microbe, but most act in many ways, which is one of their important medical applications. Oxidative stress from ROS formation, metal ion release, and non-oxidative processes are the most common metal NP antibacterial mechanisms. Direct interactions with the cell wall and membrane, cell interior penetration, nucleic acid and protein synthesis suppression, and gene expression modulation are non-oxidative processes. Metal NPs also damage bacterial biofilm, preventing bacterial cells from using an essential resistance mechanism [78]. Pathogens acquire antibiotic resistance in several ways. They include: (a) active efflux of antibiotics from bacteria through efflux pump overexpression, (b) acquisition of alternative metabolic pathways to those inhibited by the drug, (c) decreased bacterial cell wall permeability that restricts antimicrobial access to target sites, (d) degradation of the antibiotic, (e) enzymatic modification, (f) target modification, (g) overproduction of the target enzyme, and (h) transfer of antimicrobial resistance genes via quorum sensing within members of a biofilm consortium [79].

Antimicrobial nanomaterials function similarly to antibiotics by using one or more mechanisms to inhibit the growth of microorganisms or kill the invading organisms [80]. The inhibitory mechanism of the NPs is inadequately assembled and not properly explained. Nevertheless, sufficient data indicate that induced oxidative stress, the release of metal ions, and other non-oxidative mechanisms have been thoroughly studied in many models [81], [82]. In addition, microbial cell wall penetration, ROS formation, DNA and protein degradation, and cellular integrity loss are the mechanisms that inhibit bacteria, fungi and viruses. Cell penetration is commonly the first step in microbial cell inhibition, before other mechanisms are used. Adsorption of NPs at cell surfaces is the main penetrating mechanism and can occur when NPs bind to negatively charged protein functional groups, causing protein degradation and cell death [83]. A prior study indicates that ROS can arise within pathogenic cells through the mechanism of diffusion or adsorption [84].

4.2 Antibacterial Properties

The antibacterial activity of green composite nanomaterials is dependent upon various factors, including the concentration of antibacterial compounds, the method of incorporation, and the specific bacteria being targeted. Furthermore, it is crucial to consider the enduring stability and potential environmental impacts of these materials when evaluating their practical application. The GPE-AgNPs/Kaolin composite nanomaterials showed significant antibacterial activity against various pathogenic microbes, including *E. coli* and *B. subtilis* [85], and GG/Gl/Ag-N-composite materials can exhibit greater antibacterial activity against *S. aureus*, *E. coli*, and *P. aeruginosa* [86]. The interactions between NPs and bacterial cells, as well as their antibacterial properties, have been thoroughly investigated using different green synthesised NPs and various strains of pathogenic bacteria. These studies are summarised in Tables 1 and 2.

Previous research has revealed that NPs of ZnO, MgO, NiO, AlO, and also composite oxides of Mg-NiO and Al-ZnO, could be produced using *Ocimum basilicum* extract and can exhibit a significant inhibitory effect against pathogenic bacteria [87]. The antibacterial mechanism of green composite nanomaterials and NPs is shown in Figure 3. This figure outlines the proposed antibacterial mechanisms of green composite nanomaterials (NPs) and NCs against bacterial cells. The figure demonstrates how NPs and NCs exert their antibacterial effects through various mechanisms: disrupting the electron transport chain and proton motive force, damaging the peptidoglycan layer, and breaking the cell membrane. In addition, NPs and NCs generate oxidative stress by producing ROS, which leads to DNA damage and protein denaturation. They also inactivate bacterial enzymes and cause ribosome disassembly, ultimately disrupting essential cellular processes and causing cell death. These mechanisms highlight the multifaceted approach of NPs and NCs in combating bacterial infections.

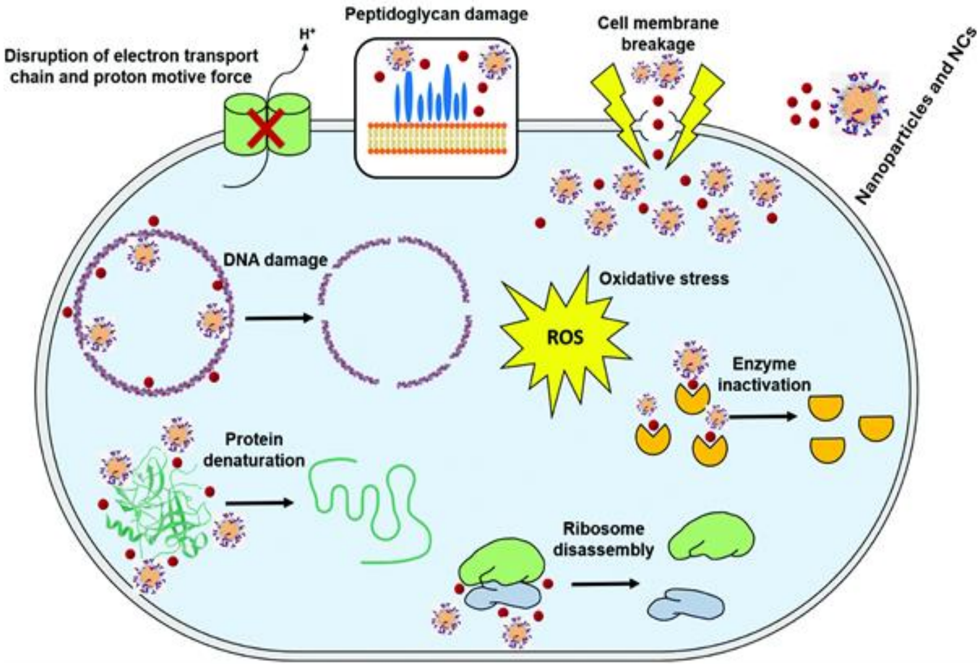

Figure 3: Antibacterial mechanisms of NPs and NCs against bacterial cells

4.3 Antifungal Properties

Green composite nanomaterials with antifungal properties have gained attention owing to the increasing demand for environmentally friendly and sustainable solutions in various fields, including agriculture, medicine and packaging. Prior research indicates that ZnO-NPs synthesised using *Beta vulgaris* can show antifungal activity against *A. niger*, while those synthesised using *Cinnamomum tamala* exhibited strong activity against *C. Albicans* [88]. A previous study indicates that ZnO-NPs using the leaf extract of *Mussaenda frondosa* can show antifungal activity against *C. Albicans* [89]. Previous studies have indicated that plant extract from pomegranate peels (PPE), chitosan nanoparticles (NCT), PPE-synthesised SeNPs, and their innovative NCs NCT/PPE/SeNPs can function as antifungal mechanisms against *P. digitatum* and edible coatings to eliminate postharvest fungal pathogens [90]. In a previous study, green-synthesised AuNPs using *Allium sativum* aqueous extract showed antifungal activity against *Candida* species due to increased production of ROS by candidal cells [61].

Figure 4 shows the antifungal mechanism of action of the green composite and NPs. This figure illustrates the antifungal mechanisms of action for NPs and NCs. In panel A, several mechanisms involved in the interaction between antifungal nanomaterials and fungal cells are highlighted. First, membrane disruption and permeabilisation occur when NCs and NPs disrupt the fungal cell membrane, leading to increased permeability and eventual cell death. The second mechanism, surface smoothing to inhibit microbial adhesion, shows how nanomaterials smooth the fungal cell surface, preventing microbial adhesion. The third mechanism, removal of ions for conidial germination, highlights how certain NPs alter surface characteristics to remove ions required for fungal spore germination. Finally, membrane intercalation and disruption are illustrated, where polyquaternium-1, a polymeric nanomaterial, integrates into the fungal cell membrane, causing disruption and cell leakage.

In panel B, the figure shows the intracellular effects of NPs. NPs enter the fungal cell through endocytosis or diffusion, allowing them to interact with cellular components. Once inside, NPs cause DNA damage, impairing the replication and transcription processes necessary for fungal survival. In addition, NPs generate ROS, leading to oxidative stress within the cell. This results in mitochondrial dysfunction, further damaging the fungal cell. Finally, NPs activate apoptotic pathways by releasing pre-apoptotic proteins, contributing to fungal cell death. These combined mechanisms illustrate the effective antifungal properties of NCs and NPs.

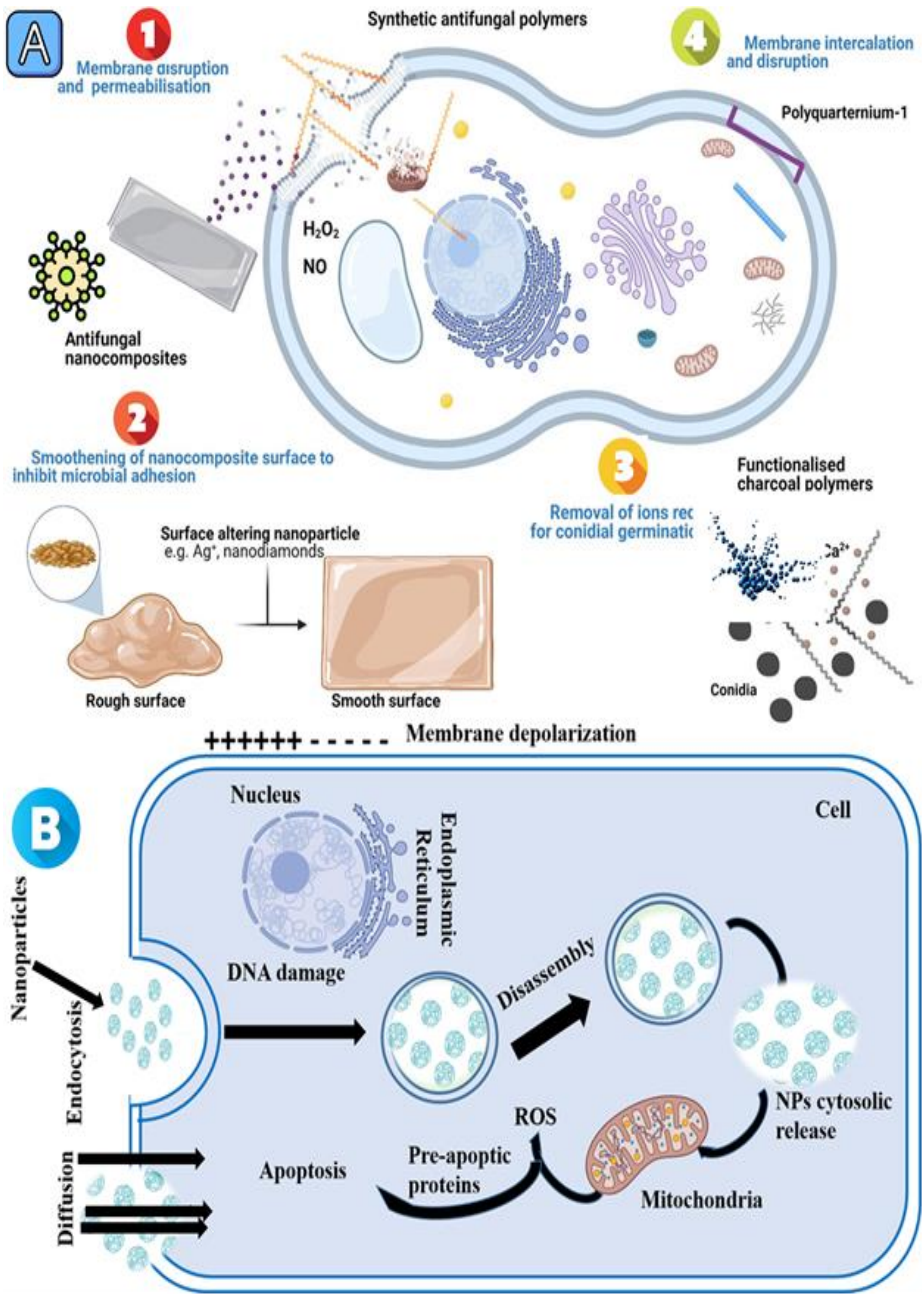

Figure 4: Mechanisms of antifungal action of NPs and NCs

4.4 Antiviral Properties

The potency of green composite nanomaterials in combating viruses depends on several factors, such as the type of antiviral drug used, its concentration, and the specific viruses being targeted. Furthermore, it is imperative to consider the long-term durability, security, and biological significance of these materials while considering their practical uses. The search for novel and potent antiviral agents is an important part of modern medicine. Antiviral activities of green-synthesised NPs produced through biological methods have been commonly used [91]. The mechanism of their antiviral impacts is still being studied, with proposed mechanisms including virus formation inhibition, blocking host cell attachment, and viral particle replication [92]. Green synthesised silver NPs showed antiviral potential against SARS-CoV-2, HIV type 1, herpes simplex virus (type 1 and 2), and human parainfluenza virus type 3 [93]. Previous research suggests that both silver NPs and silver nanoclusters (Ag-NC) showed dose-dependent antiviral activity against the herpes simplex virus, adenovirus and Coxsackie B virus [94].

Figure 5 shows the antiviral mechanism of action of the green composite and NPs. This figure illustrates the antiviral mechanisms of NPs and NCs against viral infections. The left side of the figure highlights the process of viral infection, where virus particles bind to and penetrate the host cell, entering the cytoplasm and releasing their genome. During this phase, viral replication occurs, facilitated by both viral factors and cellular factors. On the right side, the figure depicts how metal NPs and NCs exert their antiviral activity by interacting with viral surface glycoproteins, preventing viral entry. NPs and NCs also block viral replication within the host cell, inhibiting the virus from propagating. These antiviral actions demonstrate the potential of NPs and NCs in combating viral infections through multiple mechanisms.

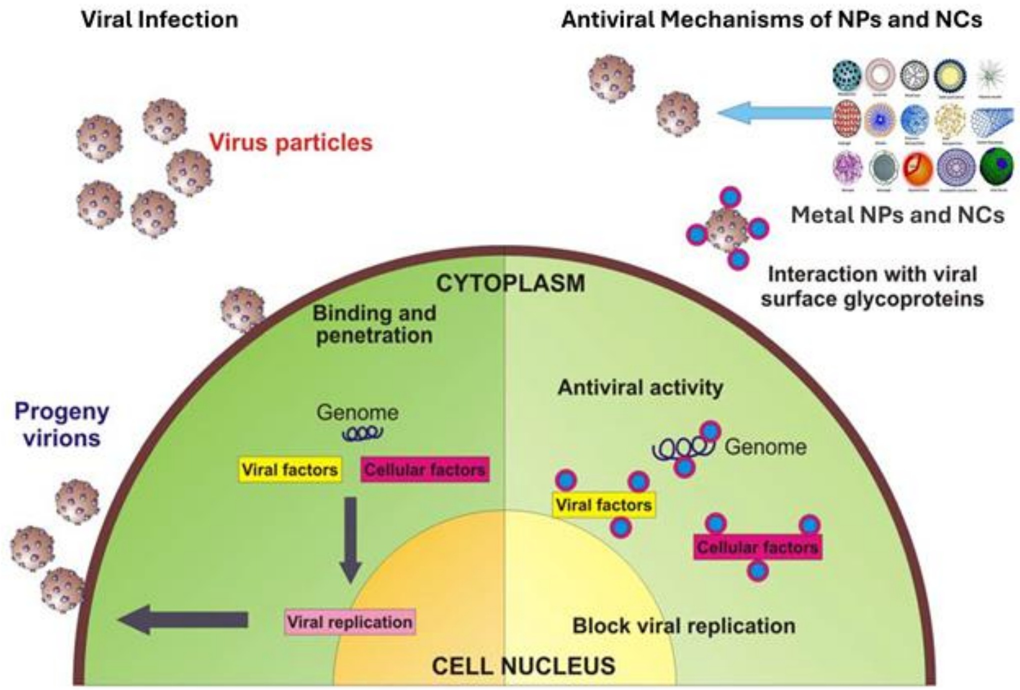

Figure 5: The mechanism of actions of antiviral activity of NPs and NCs

5 Limitations of Green Synthesised Nanoparticles and Nanocomposites

Green-synthesised NPs and NCs have emerged as promising materials owing to their eco-friendly production methods and antimicrobial properties. However, despite their advantages, several limitations need to be addressed to ensure their safe and effective use in various applications. These challenges primarily stem from production methods, human exposure risks, environmental impacts and regulatory uncertainties.

5.1 Production and Environmental Impact

Green synthesis of NPs using biological sources such as plants, fungi, bacteria and algae offers a more sustainable alternative to traditional chemical processes. However, scaling up these methods to industrial levels presents several challenges. Optimising synthesis parameters such as NP size, shape and biological activity is essential to achieving uniformity and reproducibility in large-scale production. Although green synthesis reduces the environmental impact associated with chemical methods, there are still challenges regarding resource efficiency, waste management and cost-effectiveness in large-scale manufacturing. Further research is needed to improve the scalability of green synthesis methods and address economic and environmental concerns [7], [95].

5.2 Realistic Exposure/Dose in Intended Applications

The exposure levels and doses of green-synthesised NPs and NCs in practical applications such as wound dressings, food packaging and agriculture remain poorly defined. In medical applications such as wound dressings, it is crucial to control the release of NPs to avoid potential cytotoxicity while maintaining their antimicrobial properties. Similarly, in food packaging, preventing the migration of NPs into food is essential to protect consumer health. In agricultural applications, the environmental exposure of these materials needs to be monitored to avoid unintended effects on ecosystems. Determining the realistic exposure levels of these materials is critical to ensure their safety in real-world applications [96], [97].

5.3 Leaching of Ions/NPs from Composite Matrices

A significant concern with green composite nanomaterials is the potential leaching of metal ions or NPs from the composite matrix. Despite their stability, NCs can degrade under certain environmental conditions, such as variations in temperature, pH levels or exposure to moisture. This degradation can result in the release of potentially toxic ions or NPs, posing risks to both human health and the environment. For instance, silver NPs, commonly used in wound dressings, can release silver ions, which possess antimicrobial properties but may also cause cytotoxicity at high concentrations. Therefore, it is vital to assess the stability of these composites and the potential for ion or NP leaching under realistic usage conditions [98], [99].

5.4 Standardised Cytotoxicity/Ecotoxicity Panels and Chronic Endpoints

Although many in vitro studies evaluate the short-term cytotoxicity of green-synthesised NPs and NCs, the long-term effects of chronic exposure remain poorly understood. Studies focusing on genotoxicity, immunotoxicity and bioaccumulation are lacking. The potential for green NCs to cause long-term harm to human cells, tissues and organs must be thoroughly investigated. Similarly, the impact of these materials on ecosystems, particularly aquatic life and soil health, is not well documented. To ensure the safe use of these materials, standardised cytotoxicity and ecotoxicity testing panels, including chronic exposure studies, are necessary to evaluate the long-term health and environmental risks of green-synthesised NPs and NCs [100], [101].

5.5 Regulatory Guidance and Standards

The regulatory landscape for green-synthesised NPs and NCs is still developing. In the European Union, nanomaterials are subject to regulations under the REACH framework, which requires manufacturers to provide safety data for nanomaterials. However, the application of these regulations to green composites is not well defined, as the composition and behaviour of these materials vary. In the United States, the FDA has provided some guidelines for nanomaterials used in food and medical products, but comprehensive standards for green NCs are still lacking. Clear, standardised regulatory guidelines are crucial to ensure the safe application of these materials, especially in critical sectors such as healthcare, food packaging and agriculture [102], [103].

5.6 Specific Testing for Composites

There are several key areas where testing remains insufficient. Long-term toxicity studies, particularly on chronic effects of these materials in medical, agricultural and food-related contexts, are essential. The ecological risks posed by the degradation products of green NCs require further investigation. Standardised safety evaluation protocols that are internationally recognised must be developed to ensure consistent testing across regions. In addition, regulatory harmonisation is needed to facilitate the safe use of green-synthesised NPs and NCs across different markets and applications [104], [105].

5.7 Scalability and Waste Management

Although green synthesis methods are more sustainable than traditional chemical processes, scaling them for industrial use involves challenges such as optimising raw material sourcing, maintaining consistency in NP properties, and improving production efficiency [106]. Effective waste management strategies are necessary to ensure that large-scale production does not negatively affect the environment. Furthermore, the economic viability of green synthesis methods at scale must be addressed to ensure these processes are cost-competitive with traditional manufacturing methods [107]. Despite these challenges, green-synthesised NPs and NCs offer significant promise, and ongoing research will be crucial to overcoming these obstacles.

6 Conclusion

The current review provides a comprehensive overview of green NCs and nanomaterials by using plant extracts, bacteria, fungi, algae, etc. It focuses on properties and applications of green composite nanomaterials with their antibacterial, antifungal and antiviral activities and also their mechanisms of action, with a particular focus on the correlation between the antimicrobial activities and the source of the NPs. In conclusion, NCs and nanomaterials with antibacterial activity against bacteria, fungi and viruses are a major step towards dealing with microbial infections. The NCs compositions' use of sustainable and eco-friendly materials shows environmental responsibility and opens new uses. These green composite nanomaterials have shown antibacterial activity against a wide range of microbes, showing their potential to fight pathogenic pathogens.

Natural polymers, NPs and bioactive chemicals work together to prevent microbial development. NPs are highly effective against various diseases, including multidrug-resistant bacteria, which make them valuable in medical applications. However, despite their potential, challenges related to toxicity, biocompatibility, stability and large-scale production must be addressed to ensure their safe and practical implementation. The broad range of potential applications for NPs requires an extensive understanding of their interactions with humans and the environment, as well as their overall impact at both local and global levels. Future research must therefore focus on optimising synthesis methods, improving material characterisation, and ensuring long-term environmental and health safety. Overall, this review highlights that green composite nanomaterials hold great promise as next-generation antimicrobial agents owing to their sustainability, cost-effectiveness and efficiency, which make them strong alternatives to conventional chemical-based materials. By summarising current progress and identifying existing research gaps, this work contributes to guiding future developments toward safe, scalable and application-oriented green nanotechnology solutions.

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