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Microbial Resistance: A Comprehensive Review on the Emerging Role of Bionanomaterials

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Abstract

Microbial resistance to conventional antimicrobial agents has emerged as one of the most critical global health challenges of the 21st century. The rapid evolution of resistant bacterial, fungal, viral, and parasitic strains has significantly reduced the effectiveness of existing antibiotics, leading to increased morbidity, mortality, and healthcare costs worldwide. Factors such as the overuse and misuse of antibiotics, poor infection control practices, and limited development of new antimicrobial agents have accelerated this crisis. In this context, bionanomaterials have gained considerable attention as innovative and promising alternatives to traditional antimicrobial therapies. Bionanomaterials, derived from biological sources or synthesized using green chemistry approaches, exhibit unique physicochemical properties such as nanoscale size, large surface area, enhanced bioavailability, and multifunctional mechanisms of action.

These materials can effectively combat microbial resistance through mechanisms including membrane disruption, reactive oxygen species generation, inhibition of biofilm formation, and targeted drug delivery. This review provides a comprehensive overview of microbial resistance, its underlying mechanisms, and the limitations of current antimicrobial strategies. Furthermore, it critically discusses the role of bionanomaterials—including metallic nanoparticles, polymeric nanoparticles, lipid-based nanocarriers, and phytochemical-loaded nanostructures—in overcoming antimicrobial resistance. Recent advances, challenges, safety concerns, and future perspectives of bionanomaterial-based antimicrobial strategies are also highlighted. The review emphasizes the potential of bionanomaterials as next-generation therapeutics to address the growing threat of microbial resistance.

Keywords: Microbial resistance, antimicrobial resistance, bionanomaterials, nanoparticles,

Introduction

Microbial resistance, also referred to as antimicrobial resistance (AMR), occurs when microorganisms evolve mechanisms that enable them to survive exposure to antimicrobial agents that were previously effective against them. This phenomenon has become a major public health concern, threatening the successful prevention and treatment of a wide range of infectious diseases. According to the World Health Organization (WHO), antimicrobial resistance is among the top ten global public health threats facing humanity (World Health Organization, 2023).

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The discovery of antibiotics revolutionized modern medicine and dramatically reduced mortality from infectious diseases. However, the excessive and inappropriate use of antimicrobial agents in human medicine, veterinary practice, agriculture, and aquaculture has accelerated the emergence of resistant strains. Pathogens such as *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Mycobacterium tuberculosis*, and *Candida* species have developed resistance to multiple drugs, complicating treatment regimens and leading to therapeutic failures (Prestinaci et al., 2015).

Conventional strategies to address microbial resistance, including the development of new antibiotics and combination therapies, have shown limited success due to high costs, long development timelines, and rapid resistance development. Consequently, innovative approaches are urgently needed. Nanotechnology, particularly the use of bionanomaterials, has emerged as a promising field offering novel solutions to combat resistant microorganisms. Bionanomaterials combine the advantages of nanotechnology with biological compatibility, sustainability, and multifunctionality.

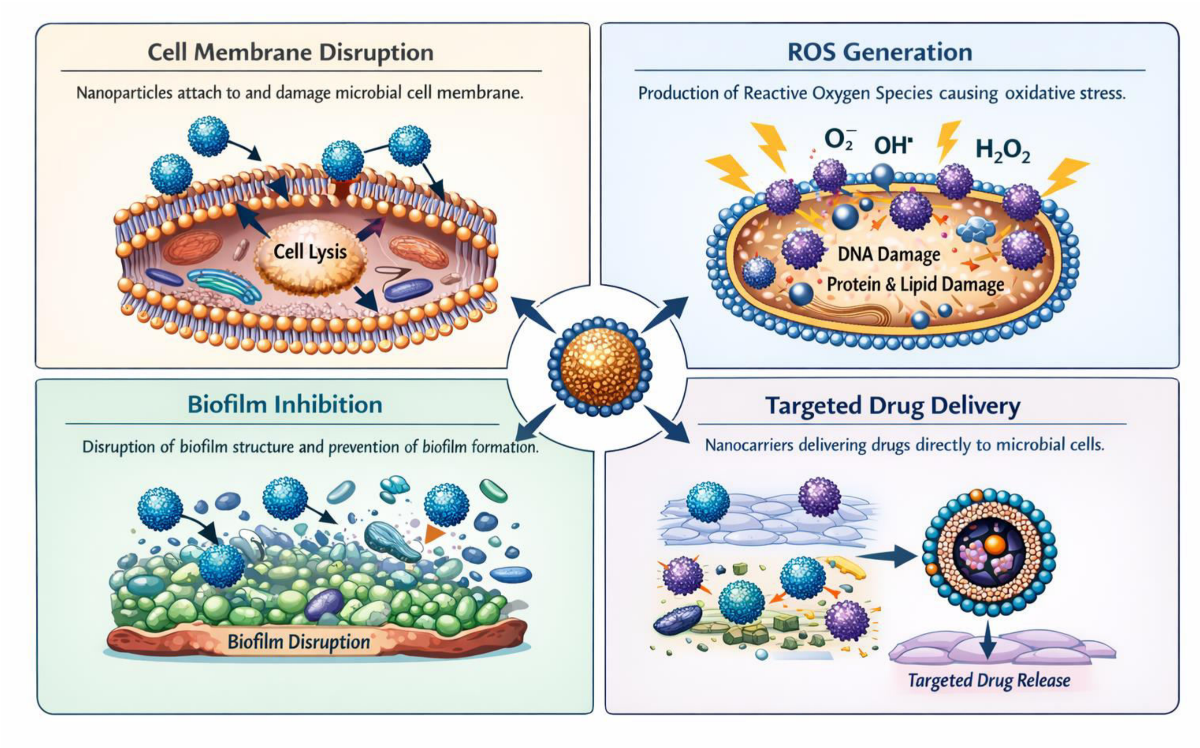

Fig. 1: Mechanism of Antimicrobial Action of Bionanomaterials

Mechanisms of Antimicrobial Action of Bionanomaterials

Bionanomaterials combat microbial resistance through multiple pathways:

Cell Membrane Disruption

Nanoparticles interact with microbial cell membranes, causing structural damage and increased permeability, leading to cell death.

Generation of Reactive Oxygen Species (ROS)

Metallic nanoparticles induce oxidative stress by generating ROS, which damage proteins, lipids, and nucleic acids.

Inhibition of Biofilm Formation

Bionanomaterials can prevent biofilm formation or disrupt established biofilms, enhancing antimicrobial penetration.

Targeted Drug Delivery

Nanocarriers improve drug solubility, stability, and targeted delivery, reducing systemic toxicity and required dosage.

Table 1: Phytochemical-Based Bionanomaterials and their Applications

Phytochemical	Type of Bionanomaterial	Source Plant	Key Biological Activities	Applications	References (APA)
Curcumin	Polymeric nanoparticles, liposomes, solid lipid nanoparticles	*Curcuma longa*	Antibacterial, antifungal, antioxidant, anti-inflammatory	Treatment of drug-resistant bacterial infections, wound healing, biofilm inhibition	Anand et al., 2007; Gupta et al., 2019
Quercetin	Nanoemulsions, polymeric nanoparticles	*Allium cepa*, *Camellia sinensis*	Antimicrobial, antiviral, antioxidant	Control of MDR bacteria, anti-biofilm therapy, oral infections	Donsì et al., 2011
Naringin	Chitosan nanoparticles, lipid nanoparticles	*Citrus paradisi*	Antibacterial, anti-inflammatory	Dental infections, gastrointestinal infections, drug delivery	Sharma et al., 2020
Resveratrol	Liposomes, PLGA nanoparticles	*Vitis vinifera*	Antibacterial, antifungal, antioxidant	Skin infections, wound dressings, food preservation	Santos et al., 2019
Epigallocatechin gallate (EGCG)	Metallic and polymeric nanoparticles	*Camellia sinensis*	Broad-spectrum antimicrobial, anti-biofilm	Medical device coatings, oral hygiene products	Steinmann et al., 2013
Berberine	Solid lipid nanoparticles, polymeric nanoparticles	*Berberis vulgaris*	Antibacterial, antifungal	Treatment of resistant *Staphylococcus aureus*, gastrointestinal infections	Li et al., 2015
Thymol	Nanoemulsions, lipid nanoparticles	*Thymus vulgaris*	Antimicrobial, antifungal	Food packaging, topical antimicrobial formulations	Marchese et al., 2016
Eugenol	Polymeric nanoparticles, nanoemulsions	*Syzygium aromaticum*	Antibacterial, antifungal	Dental applications, wound care, antiseptic formulations	Pramod et al., 2010
Allicin	Lipid nanoparticles	*Allium sativum*	Antibacterial, antifungal	Respiratory infections, food preservation	Borlinghaus et al., 2014
Piperine	Solid lipid nanoparticles	*Piper nigrum*	Antimicrobial, bioavailability enhancer	Combination therapy for resistant infections	Gorgani et al., 2017

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Role of Bionanomaterials in Overcoming Resistance

Metallic Nanoparticles

Silver nanoparticles (AgNPs) are widely studied for their broad-spectrum antimicrobial activity. They exhibit multiple mechanisms of action, reducing the likelihood of resistance development (Rai et al., 2012).

Polymeric Nanoparticles

Chitosan-based nanoparticles possess inherent antimicrobial properties and can be used as drug carriers.

Lipid-Based Nanocarriers

Liposomes and solid lipid nanoparticles enhance drug penetration into microbial cells and biofilms.

Phytochemical-Based Bionanomaterials

Nanoformulations of curcumin, naringin, quercetin, and other phytochemicals demonstrate improved antimicrobial efficacy and stability.

Conclusion

Microbial resistance poses a serious threat to global health, necessitating the development of innovative therapeutic strategies. Bionanomaterials offer a promising solution by combining nanoscale advantages with biological compatibility and multifunctional antimicrobial mechanisms. Their ability to target resistant pathogens, disrupt biofilms, and enhance drug delivery positions them as potential next-generation antimicrobial agents. However, challenges related to safety, scalability, and regulation must be addressed to fully realize their clinical potential.

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