Nano-Antibacterial Materials as an Alternative Antimicrobial Strategy

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Abstract – Bacterial infections continue to be a leading cause of death and disability worldwide. Considering the increment in bacteria resistant to antibiotic and the prevalence of illnesses linked to biofilms, it is imperative that new strategies of killing bacteria be developed. As a result, recent years have seen a surge in interest in nanoparticle-based materials for use in antimicrobial chemotherapy. Bacterial infections have remained a significant source of death and morbidity, despite the availability of many powerful antibiotics and other antimicrobial measures. Because of rising worries about drug-resistant bacteria and diseases linked to biofilms, there is an urgent need to create new bactericidal techniques. As a result, the science of antimicrobial chemotherapeutic has focused heavily on recently developed nanoparticle-based materials. Nanoparticles are discussed in this article in terms of their antimicrobial properties, their method of action, their influence on drug-resistant microorganisms, and the hazards associated with their usage. Nanoparticles' special characteristics and their mode of action as antimicrobial properties are examined in depth, as are the factors that contribute to their performance in a clinical environment.

Keywords – Nano-Antibacterial Materials, Nanoparticles, Organic Nanoparticles, Inorganic Nanoparticles.

I. INTRODUCTION

Surfaces are common places for bacteria to live in both clinical and industrial environments. While most studies in contemporary microbiology examine single-species free-swimming planktonic (pure-culture) bacteria, it is presently accepted that the vast majority of bacteria really reside in communities of microorganisms. The negative effects of bacterial surface contamination—the bacteria's ability to stick to and remain in a surface's texture—are becoming better acknowledged. According to Diskin [1], greater morbidity and healthcare costs are experienced by patients due to biofilm-related infectious illnesses that account for more than 80% of the overall microbial illnesses in the human body.

Microorganisms may band together to form what are called biofilms, which attach to surfaces. Bacteria attach themselves irreversibly to surfaces after first attaching to them in a reversible fashion through the secretion of binding molecules such adhesion proteins. Once the bacteria have established themselves, they multiply and colonise inside the peptidoglycan envelopes, maturing the biofilms. At this juncture, bacteria are not just resistant to antibiotics and the immune system of the body, but they also act as a bacterial source for systemic chronic illnesses. This is why biofilms pose such a serious risk to human health. Biofilms may also become resistant to antibiotics, which are often ineffective against them. Because of this, bacterial infections remain a problem even if there are many effective antibiotic medications and other contemporary antibacterial measures available.

There are a number of issues with current antimicrobial materials used in clinical settings, including insufficient antimicrobial activity, the potential for germ resistance, challenges in monitoring and prolonging antimicrobial capabilities, and the inability to adapt to changing conditions. Thus, there is a critical demand in the medical and dental fields for materials that are both powerful against germs and resistant to biofilms. Since no other effective methods exist at present, antibiotics are often used to treat infections caused by biofilms. Nonetheless, it is well recognised that standard antibiotics fail when used to combat mature biofilms; that is, significantly larger than typical medication dosages are necessary, since all such drugs have difficulties permeating the intracellular polysaccharides sheath enveloping the biofilm. Antibiotics have a far lower success rate in treating infections caused by bacteria that have formed a biofilm, which may be anywhere from 100 to 1,000 times more resistant to these drugs than planktonic germs.

Furthermore, conventionally utilised lower doses are ineffective, and high concentrations are frequently not tolerated by the host organism. Furthermore, there is a significant danger of viable bacteria becoming resistant to conventional

antibiotics when they are used. When multiple antibiotics are employed to combat a diverse microflora, the problem becomes even more convoluted because of the resulting mixed bacterial biofilms. This necessitates a variety of antimicrobial precautions. The physicochemical attributes of many different materials can be modified using modern nanotechnology to create effective antimicrobials. Due to their enormous surface area in relation to their size, nano-materials (NM) could be tactically beneficial as active groups of anti-bacteria. Although only a tiny amount of nanoparticles are used, they may provide a large amount of activity. As a result, NM has the potential to replace antibiotics in the treatment of bacterial illnesses. Maxillofacial prosthesis has been demonstrated to generate biofilms, which increase the incidence of tissue inflammation around the prostheses, when exposed to a diverse external environment with a range of flora. Nano-titanium dioxide, when applied on prosthesis, inhibits the growth of microorganisms when exposed to light. **Fig 1** provides another illustration of the clinical use of antimicrobial NPs.

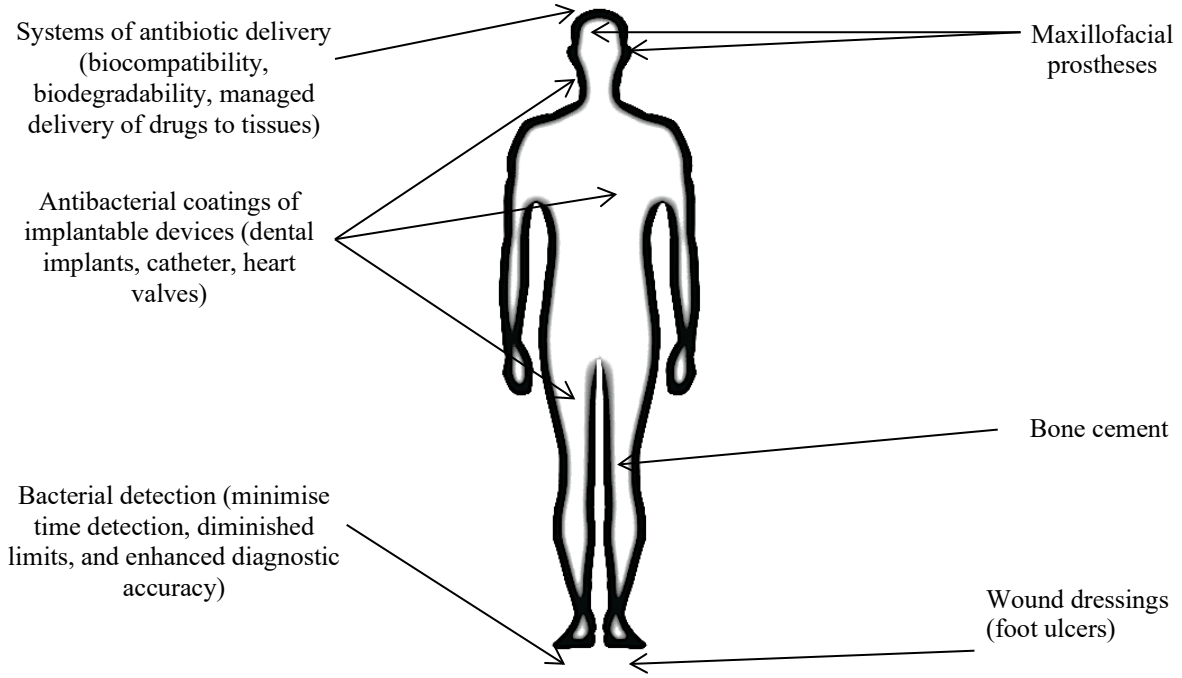

Fig 1. NPs' Use as an Antibacterial Agent

Antibiotics are used to kill bacteria by interfering with their ability to make cell walls, translate their own genes, or replicate their own. However, it is possible for bacteria to evolve resistance to each of these strategies of action. In addition to efflux pumps, which offer multidrug resistance to different antibiotics, other mechanisms of susceptibility integrate enzymes, which change or breakdown the antibiotic, like glycopeptides and actamases, modifications of major cell elements, such as cellular walls, as indicated in golgi apparatus and vancomycin resistance within the etracycline resistance. As nanoparticles kill bacteria mostly by physical contact with the cell wall rather than by penetrating it, many of the strategies of resistance identified in antibiotics are rendered moot. This gives us reason to believe that nanoparticles are less likely to foster resistant bacteria than antibiotics.

This article discusses the potentials of nano-antibacterial materials as effectual and alternative antimicrobial strategy. In the process, the actionable antibacterial mode of nanoparticles is explained, along with their interconnections with microbial cells that ultimately result in cell death, and their toxic and biocompatibility features. Here is how the article is structured: Section II focuses on an evaluation of antimicrobial nanoparticles. Section III and Section IV review inorganic nanoparticles and organic nanoparticles respectively. Section V presents final remarks regarding the article.

II. ANTIMICROBIAL NANOPARTICLES

As Nanoparticles (NPs) are increasingly being used in healthcare, researchers have been investigating their possible antibacterial actions. Metal NPs may affect bacterial metabolism. This ability holds great promise for the eradication of microorganisms in the treatment of illness. The capacity of NPs to infiltrate biofilms offers a realistic approach to preventing biofilm development via the suppression of gene expression caused by the presence of Ag. For NPs to kill bacteria, they must come into physical touch with the microbes. The van-der-Waals, electrostatic attractions, hydrophobic attraction, and the receptor, and ligand linage are all recognised types of contact. The NPs subsequently diffuse across the bacteria cellular membrane and congregates within the metabolic pathways, where they alter membrane structure and function. Then, the NPs cause heterogeneous modifications, transformation in the permeability of cellular membrane, oxidative stress, protein deactivation, enzyme inhibition, electrolyte balancing abnormalities, and variations in the expression of genes by linking up with key elements of bacterial cells such enzymes, lysosomes, ribosomes, and DNA.

Current studies mostly suggest the following processes: non-oxidative strategies, oxidative stress, and the metal-ion release.

Oxidative stress

One key antibacterial attributes of NP is the ROS-induced oxidative stress. As oxygen molecules are reduced by NPs, a variety of reactive oxygen species (ROS) are produced. ROS refers to an all-inclusive acronym for reactive intermediates and elements comprising of high-positive redox potentials. Singlet oxygen (O_2), superoxide radicals (O_2), hydrogen peroxide (H_2O_2) and hydroxyl radicals (•OH) are the four types of ROS, each of which is dynamic and active to varying degrees. Calcium and magnesium oxide NPs, for instance, may produce O_2, but zinc oxide NPs can produce just OH and H_2O_2. NPs composed on Copper oxide, meantime, may generate all four reactive oxygen types. Guo et al. [2] shows that whereas OH and O_2 may induce immediate microbial mortality, H_2O_2 and O_2 produce less severe stress responses and can be mitigated by antioxidant systems such as catalase and superoxide dismutases. Reorganization, defect sites, and hydroxyl radicals in the crystal all contribute to ROS generation. In a typical bacterial cell, ROS generation and removal are in equilibrium. When ROS generation is high, however, the cell's redox balance shifts in favour of oxidation. This imbalance results in oxidative stress that destroys the parts of bacterial cells.

Dissolved metal ions

In order to inhibit microorganisms, metal ions must be slowly discharged from metal oxides, assimilated through the cellular membranes, and then interact directly with the organic compounds of nucleic acids and proteins, including mercapto (-SH), carboxyl (-COOH) groups, and amino (-NH) causing disruptions in enzyme activity, alterations to cell structure, disruptions to typical physiological functions, and ultimately inhibition. The suspension of metal oxides has flawed the activity of antimicrobials since metal ions are known to have minor effects on the lipid vesicles pH. Consequently, metal ions in solution are not the primary mechanism by which metal oxide NPs exert their antimicrobial effects. Another study demonstrated that superparamagnetic iron oxide also penetrates bacterial cell membranes and disrupts transmembrane electron transfer in its interactions with microorganisms. Indirectly transporting antimicrobial substances, heavy metal ions have also been studied.

Non-oxidative mechanisms

In [3], authors have investigated the strategies of antibacterial in MgO by employing techniques such as Fourier transform infrared (FTIR), tools of proteomics, electron spin resonance, transmission electron microscopy (TEM); liquid chromatography mass spectrometer, and flat cultivation. Under ultraviolet (UV) light, direct sunlight, or total darkness, three distinct MgO NPs show potent antibacterial activity against E. coli. These NPs' antibacterial actions are independent of oxidative stress-induced membrane lipid peroxidation for three reasons: whenever the bacteria cellular membranes have been pierced and the pores to the surface are visible, MgO NPs are not visible with cells.

In addition, spectra obtained via energy-dispersive X-ray spectroscopy show no evidence of an abundance of Mg ions. Hence, MgO's inhibiting impact causes membrane damage to cells. Two varieties of MgO NPs are unable to detect even trace quantities of ROS, whereas a third is capable of doing so. MgO NP treatment has no discernible effect on cell wall lipids such as phosphatidylethanolamine (PE) and. lipopolysaccharide (LPS), demonstrating that MgO does not facilitate the induction of lipid peroxidation. Moreover, the quantity of ROS-linked proteins in cells are not enhanced, but other essential protein-related cellular metabolic processes—such as glucose metabolism, nucleotide metabolism, glucose metabolism, and amino acid metabolism—are markedly slowed down.

Antibacterial nanomaterials show great promise and are attracting a lot of attention because they may be able to succeed where antibiotics have failed. Among these is the fight against biofilm and mutants that have become resistant to multiple drugs. There is a wide range of modified and intrinsic chemical composition elements among currently used antimicrobial NM (i.e. metal oxide, organic nanoparticles, and metals). This explains why they use so many different strategies (see **Fig. 2**). In addition, there is a wide variety of target bacteria, each of which has its own unique set of genes and, hence, its own unique cell wall structure, important metabolic systems, and many other components. The degree to which bacteria are affected by NM may also depend on whether they are planktonic, multilayer, rate of growth, sedentary, or starving.

The toxicity of the NM may depend on the bacteria-to-NM ratio in certain circumstances. Moreover, a variety of environmental parameters, such as air circulation, pH, and temperature, all contribute to and influence NM's bactericidal efficacy. Antibacterial activity is highly dependent on the physical qualities of particles, such as chemical modifications size, shape and coating, and combination in different proportions with solvent utilised and other nanoparticles. Due to their complexity, many aspects of NM antimicrobial action mechanism and the risk levels they pose remain unidentified, and conflicting reports can be found in the literature.

The typical mechanisms of NM are depicted in this overarching diagram. The majority of known NM antibiotics disrupt the bacterial membrane through electrostatic interactions. The interactions between NMs and membranes are a common source of free radicals (ROS yellow patches). Supplementary cellular membrane damages, DNA disruption, impaired protein functions, and an increase in radical generation are all possible outcomes of these radicals. Additional bactericidal NMs are light-activated (photocatalism). RNS is associated with nitric oxide (NO) NM (green spots).

Polycationic NM (QPEI) appears to stimulate the secretion of signals that could enhance computed cell death, making them a very special type of NM.

Nanomaterials as antibacterials

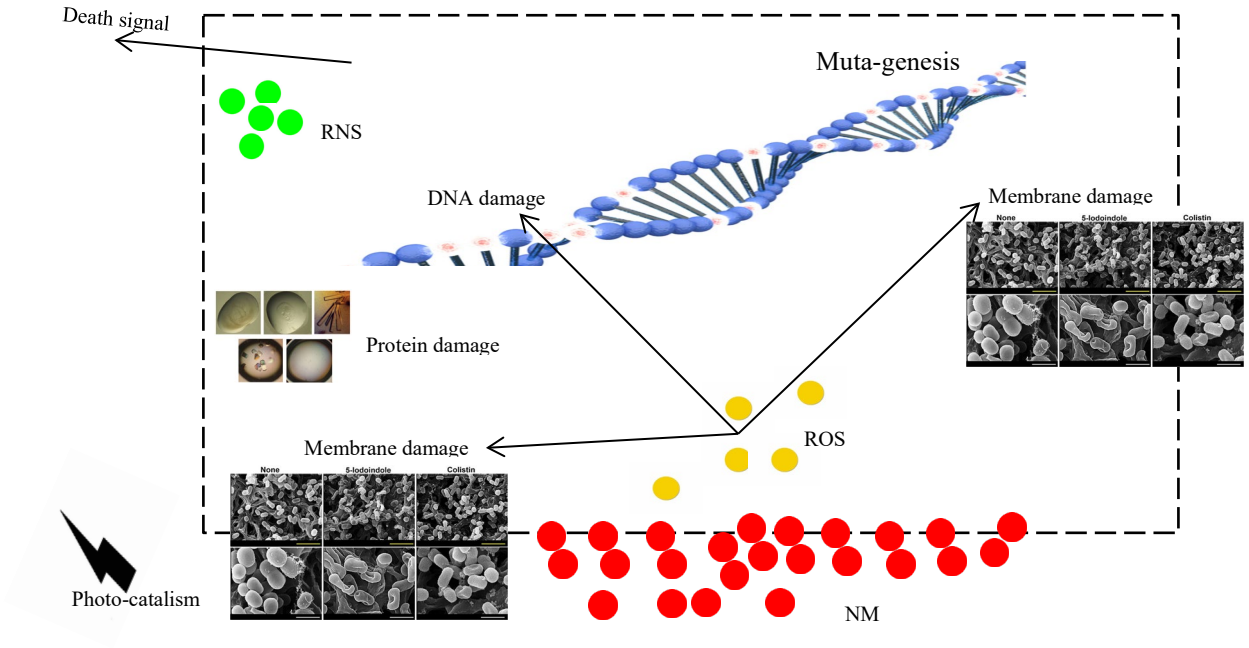

Fig 2. A Mechanism of Action for NM Antibacterial

Nevertheless, NM operates along two key deadly routes, which are connected to one another and often happen concurrently: (1) disturbance of the integrity and potential of membranes; and (2) establishment of ROS, also known as oxygen-free radical, with NMs operating as a nanocatalyst. NM cause membrane damage when they bind electrostatic interactions to the bacterial cell membranes and wall, changing the membrane potential, depolarizing the membrane, and destroying its integrity. This causes an imbalance in transport, hinders respiration, halts energy transduction and/or causes the cell to lyse and die. By disrupting the respiratory chain or inducing them directly, NMs are thought to be the most important factor in determining their cytotoxicity in vitro and in vivo.

Lipid peroxidation, protein modification, enzyme inhibition, and DNA and RNA damage are all results of the severe oxidative stress caused by a sudden influx of ROS into the cell. When present in sufficient quantities, ROS may induce cell death, whereas even trace amounts can cause significant DNA mutations and damage. The photocatalytic toxicity of NM occurs when UV or visible light stimulates the production of reactive oxygen species. Lipid peroxidation that stimulates cell death and respiratory failure in E. coli is induced by TiO2 NM when exposed to near-UV light. Direct critical enzyme inhibition, establishment of NRS (nitrogen reactive species), and activation of computed cell death are some of the additional impacts of NM.

III. INORGANIC NANOPARTICLES

There has been a lot of research on the antibacterial elements of both the metal oxides and metals, such as titanium dioxide (TiO_2), zinc oxide, iron oxide (Fe_3O_4), silver (Ag), and copper oxide (CuO), are widely used as antibacterial agents (ZnO). While certain nanoparticles of metal oxide are effective because of their establishment of ROS.

Silver

In particular, silver nanoparticles have found widespread use as an antibacterial agent due to their potency against viruses, bacteria and fungus. Their relevance was comprehended even in tradition pasts. Disinfecting medical equipment and purifying water are two of the oldest uses for silver and its compounds. Ag compounds are often used in the medical field to treat wounds, burns, and many infectious disorders. Ag, like other metals as well as metal nanocomposites, was discovered to have antibacterial activity that varied with particle size. Smaller Nanocomposites have a greater antibacterial impact than bigger ones, even if the mode of action of Ag nanoparticles is still unclear. Antibacterial activity of Ag nanoparticles is higher than that of their bulk counterparts. However, if they have a high surface energy, they are more likely to aggregate into big particles, which may diminish or even eliminate their antibacterial action.

With the discovery of penicillin and, subsequently, other antibiotics, silver (Ag) and other nonantibiotic therapies were almost forgotten. It has acquired fresh, contentious attention, however, because to the rise of antibiotic-resistant bacteria

over the past few decades. There have been numerous reports where silver is an effective bactericidal antimicrobial agent against a variety of pathogens both in vivo and in vitro. In addition, it appears that microbial are less susceptible to acquiring resistance against Ag compared to the traditional antibiotics. Nevertheless, there are still several unanswered problems and grounds of contention, including the measurements and definition of the Minimal Inhibitory Concentrations (MIC) and silver breaking points, the easiness with which a resistant strain might arise, whether silver actually affects planktonic or biofilm cells, and the harmful impacts of silver on people.

Ag-bactericidal NM's actions are also not well known. The Gram-negative bacterium E. coli was used because it is a good example of the damage that Ag nanoparticles may do to the cellular walls by enhancing the permeability of membranes and switching off the chain in respiratory systems. Banister et al. [4] have shown that the silver ion, which has a strong attraction to nitrogen and sulphur, can link up to amino and thiol groups, hence disrupting and inhibiting the structure of protein. Last but not least, it has been recommended that Ag NM are photocatalytic and have the capacity to induce reactive oxygenated species, an observation that has been refuted by other data demonstrating that, in eukaryotes, this effect is dependent on the type of cells. It was also found that Ag-NM had synergistic antibacterial impacts when given together with antibiotics, damaging more Gram-positive and –negative bacteria compared to antibiotics alone. Notwithstanding the controversy and dispute, Ag-NM may be the most efficient antibacterial metallic NMs.

Titanium Oxide

Another metal oxide with shown antibacterial activity is titanium dioxide (TiO_2). The antibacterial effects of TiO_2 on Gram-negative and -positive bacteria have been known for quite some time. Recent studies have demonstrated its effectiveness against a wide range of virus and parasite strains. There has been a long history of using titanium dioxide (TiO_2) NM as an antibacterial chemical. They are photocatalytic like Au and their toxicity is triggered by visible light, near-UV, or UV, leading to an increase in ROS production. Several bacterial macromolecules and processes, including the cell membrane and DNA, are destroyed by the ROS. Bacillus spores, the most resistant bacterium known, are killed by TiO_2, along with many other types of bacteria. Synergistic effects and increased activity were seen when combining TiO_2 or Ti with other NM, such as Ag.

Zinc Oxide

Nanoparticles made of ZnO are yet another type of broad-spectrum bactericidal NM. Antibacterial activities against different microbes were observed for ZnO nanoparticles, and it was shown that this activity varied widely depending on the concentrations and particle size used. In addition, ZnO nanoparticles were demonstrated to be efficient bactericidal elements, which were not impacted by models that are resistant to drugs of methicillin-resistance S. epidermidis and methicillins-resistant S. aureus (MRSE, and MRSA respectively). Zinc oxide (ZnO) nanomaterials (NM) are effective against many different types of bacteria in a size-dependent manner at a low cost.

Low-toxicity microorganisms include Listeria monocytogenes, Klebsiella pneumonia, Salmonella enteritidis, Lactobacillus, Streptococcus mutans, and E. coli. They are effective coating nanomaterials for clinical and other equipment because of their white hue, protection from UV rays, and inability to foster the growth of biofilms. In addition, the FDA (Food and Drug Administration) green-lighted zinc as a treatment and today Zn can be purchased as a food additive. By adhering to membranes, altering their integrity and coherence, and inducing ROS generation, ZnO NM affect bacteria cells through the two mechanisms outlined above. Furthermore, and therefore, Zn NM are mutagens, although mild ones.

Iron Oxide and Gold

Gold (Au) and Fe_3O_4 nanomaterials as another segment of antimicrobal nanomaterials are also being investigated for their potential medical applications. Laboratory tests have failed to demonstrate any antimicrobial activity for either bulk Fe_3O_4 or metallic gold (Au). The fact that these nanomaterials can be transformed to have antibacterial characteristics when synthesised as nanosized nanoparticles ups the ante. Different microbiological researches have indicated that Fe_3O_4 nanoparticle-transformed surfaces have antiadherent elements and fundamentally minimized colonization by both Gram-positive and -negative bacteria. Evidence suggests that gold nanoparticles and nanorods with photothermal functionalization can effectively eliminate bacteria.

In contrast to gold (Au-) and silver (Ag) NM are almost completely ineffective against bacteria when used alone. Attached to vancomycin, ampicillin, antibacterial enzymes lysozymes, and other NM, Au-NM killed a number of multidrug-resistance organisms, integrating those that are resistant to vancomycin and penicillin. Antibacterial activity of Au-NM was boosted by its bonding to the non-antibiotic components like citrate and amino-substituted pyrimidines. These molecules and light energy are used to induce ROS generation and mutation in cancerous cells for the purpose of therapy. One more cancer therapy that has found success against bacteria is photothermal activation of Au-NM bound to Fe_3O_4. Antibacterial NM made from gold (Au) is often preferred over NM made from other metals, such as platinum (Pt), due to their greater stability.

The majority of our understanding of Pt NM comes from studies of its effects on cancer cells, where studies have shown that Pt NM may permeate through mammalian cellular membrane and cause DNA damage, cell cycle aggregation in the S phase, and apoptosis. Nevertheless, it was only recently shown that Pt NM is poisonous to bacteria and that this toxicity scales with bacterial size. Pt NM particles between 1 nm and 3 nm in terms of size were antibacterial

to P. aeruginosa cellular membranes, but Pt NM particles between 4 nm and 21 nm in size were bacteriocompatible. In another study conducted, researchers found that the combination of Pt and Au in a bimetallic environment had a potent bactericidal effect, despite the fact that neither metal is deadly to bacteria on its own. Cell death, as stated by the authors, was the result of cellular damage and a drastic increase in ATP, which is interesting because this effect is ROS-independent compared to other NM.

Copper Oxide

Antibacterial activity of copper oxide (CuO) nanomaterials has been indicated against a wide range of bacterial pathogens; however it is slightly lower than that of Zinc oxide (ZnO), or silver (Ag). Thus, a significant amount of nanoparticles must be used to accomplish the same goals. Moreover, the activity of CuO nanoparticles varies substantially depending on the bacterial species that are put to the test. Nonetheless, Cu may be used for efficiency increase in the form of nanocomposites since it is cheaper than other nanosized metal materials.

Like other metal nanoparticles, CuO NMs attain its antibacterial actions by disrupting membranes and producing reactive oxygen species (ROS) [5]. Co NMs are typically less strong compared to Ag-NM, while the converse is true on occasion. For instance, Staphylococcus aureus and Escherichia coli were increasingly vulnerable to Ag, while Bacillus anthracis and Bacillus subtilis were vulnerable to Cu NMs. CuO NM had the highest antibacterial activity compared to other metallic MN excluding Ag-NM. These findings may be explained by the fact that bacteria like B. subtilis are more susceptible to CuO because their cell walls contain a higher concentration of amine and carboxyl groups. Hence, it seems that the CuO NM is preferable to others, including silver, under some circumstances.

Magnesium Oxide

Another kind of metal oxide NM that has been found to be antibacterial is nano-magnesium oxide (MgO). It has been observed that nano-sized MgO particles have potent antibacterial action against a massive array of micro-organisms, such as gram-negative and –positive bacteria, viruses and spores. Nano-MgO has the benefit of being made from cheap and easily accessible ingredients, making it a more attractive option than other metal nanoparticles. MgO and MgX_2 are two common forms of magnesium that find use in a wide range of Processes (e.g., MgF_2). Mg-containing NM may not only cause ROS production, but also directly block vital bacterial processes. Biofilm generation by Escherichia coli and Staphylococcus aureus was inhibited by MgF_2 NM.

Superparamagnetic Iron Oxide

The utilization of magnetic nanoparticles to penetrate and eliminate biofilms is nothing new, but the application of superparamagnetic iron oxide (SPION) [6] is. These particles generate local hyperthermia when exposed to a magnetic field, and may be layered with other NMs, such as Au and Ag, to enhance their magnetic actions.

Nitric Oxide

As NO is implicated in several modes of antimicrobial action, it poses a minimal risk of developing resistance, making nitric oxide (NO) NM an attractive antibacterial agent. Similar to other metal-oriented nanomaterials, the antibacterial activities are shape and size dependant, with the smallest materials having the highest aspect ratios. Natural nitrous oxide (NO) is a chemical that the body makes and uses in many ways. Despite its many benefits, it has limited therapeutic use because of how reactive it is. The antibacterial effects of NO, however, may be fully realized by encapsulation, controlled drug release, and localized administration. NO NM is more selective for RNS than O2 (ROS) when compared to other metal-based NMs. Research has shown that wound healing in both normal and diabetic mice is improved by NO NM and that NO NM are effective in killing MRSA (methicillin-resistant S. aureus) in skin infection. The biofilms of many different types of bacteria may be eliminated with the use of NO NM.

Aluminum Oxide

It is currently not distinguishable if Al_2O_3 (aluminium oxide) nanomaterials are good for antiseptic therapy activities. First, their bacterial activities are modest, and they only fuction at higher concentrations until integrated with other NMs like Ag. Secondly, they have the potential to encourage horizontal transmission of multiresistance genes between genera through plasmids. Aluminum NM works via diffusion and buildup within cells, producing pit development, perforation, and membrane disruption, ultimately causing the death of cells, as previously shown in E.Coli.

IV. ORGANIC NANOPARTICLES

Antibiotics, antimicrobial and antimicrobial peptides agents are released from polymeric nanoparticles, while quaternary ammonium compounds, alkyl pyridiniums, and quaternary phosphoniums are used to create cationic surfaces that kill microbes by touch. These cationic groups have been shown to disrupt the bacterial cell membrane in a variety of ways; some of these methods of action need hydrophobic chains of a certain length in order to enter and break the bacterial membrane. Regardless of the length of the hydrophobic chain, it has been demonstrated that a sufficiently strong positive charge may give antibacterial capabilities. This may occur via an ion interchange process between the charge surface and bacterial cellular membrane. For polycations to be effective against bacteria, they must bind to and interact with the

membrane in a way that is favorable to their many charges. Our results imply that positively charged surfaces based on polymers might be engineered to provide a broad variety of contact-killing compounds.

Natural organic antibacterial compounds are often regarded as less stable than inorganic antibacterial materials, especially at higher temperatures. This may create challenges in the design of goods that need to be robust and able to survive extreme processing conditions. Since then, antimicrobial compounds have increasingly been made from inorganic nanosized materials. There is now a published review that covers everything there is to know about antimicrobial polymers. What follows is a quick synopsis of the various polymers discussed in this review.

Poly-ε-lysine

The cationic L-lysine homopeptide referred to as poly-ε-lysine has demonstrated efficiency against the Gram-negative and positive microorganisms. B. coagulans spores, B. subtilis spores, and the B- stearothermophilus spores are likewise inhibited by this compound.

Quaternary Ammonium Compounds

Cetrimonium chloride, stearalkonium chloride, and Benzalkonium chloride are all examples of quaternary ammonium compounds that have found widespread use as disinfectants. Its antibacterial efficacy is proportional to the length of the N-alkyl chain that makes them lipophilic. Antibacterial activity is maximized in elements with an alkyl chain length of approximately 12 to 14 against Gram-positive bacteria, and in elements with a length of alkyl chain of 14 to 16 against Gram-negative bacteria. Electrostatic repulsion between the compound's moieties charged positively and the bacterial membrane charged negatively sets the stage for the compound's subsequent contact with the bacterial wall, where its hydrophobic tail integrates into the hydrophobic membrane core of the bacterium, denatures structural proteins, and inhibits enzyme activity.

In order to create antimicrobial polymers, 2-alkyl-1, 3-oxazolines were subjected to a cationic ring-opening polymerization, and the resulting macromolecule was terminated with cationic surfactants. Quaternary pyridinium is a nitrogen-containing heterocyclic chemical compound. The pyridinium groups within the polymer chains are responsible for its antibacterial properties. Imidazole derivatives are another class of aromatic/heterocyclic polymers used as antimicrobials. Free imidazole may collect electrostatically while losing its hydrogen bond-forming capacity to medicines and proteins, but its alkylated version (imidazolium) can establish hydrogen bonds with them. They have enhanced biodegradability, are chemically stable, and are biocompatible. Synthesized N-vinylimidazole/phenacyl methacrylate copolymers are highly antibacterial and effective against different fungus, yeasts, and bacteria.

Synthetic cationic polymers with tertiary, secondary, and primary amino functionalities, polyethyleneimine (PEI) is not biodegradable. PEI was bonded to a wide range of commercial plastics, textiles, glass, and other inorganic and organic, synthetic and natural, nano-scaled and macroscopic, porous and monolithic surface materials. Pathogenic and antibiotic-resistant bacterial and fungal strains were killed on these immobilized surfaces without any reports of resistance developing. The reported mechanism of antibacterial activity is cell membrane disruption. Mammalian cells may safely attach to and grow on these surfaces. In addition to having potent bactericidal action against different Gram-positive and – negative micro-organisms that are airborne, N-alkylated PEI immobilized over polyester, wool and cotton all display similar properties. The Mw of PEI has a major impact on the performance.

Prosthesis degradation in laryngectomy patients poses a significant risk due to the usage of substituted PEIs against Candida albicans. Due to their high water solubility, outstanding biocidal effectiveness, broad antibacterial range, and nontoxicity, polybiguanides and polyguanidines constitute a fundamental antimicrobial polymer family. Due to their electrostatic interaction with cell membranes, acrylate monomers containing pendant biguanide groups have potent antibacterial activity. Several oligomeric guanidines have been produced via polycondensation of guanidinium salts with four distinct diamines under varied circumstances. Each series contains linear compounds that are distinguished from one another by the number of guanidine and amino groups at the end (type A), the number of type B amino groups, of type C guanidine groups. Antimicrobial efficacy requires molecules with a mean molecular mass of approximately 800 Da.

Cationic Quaternary Polyelectrolytes

Acrylates and methacrylates are the most common types of cationic quaternary polyelectrolyte employed as an antimicrobial polymer, with many of these compounds being produced from commercialized poly(acrylics monomers like 2-(dimethylamino)ethyl acrylics. Hydrophobicity, molecular weight, and surface charge are only a few of the structural characteristics that may be tuned to increase or decrease the polymers' structural adaptability.

N-Halamine Compounds

When halogenated imide, amine groups, or amides are combined, the resulting N-halamine compounds are stable and slowly emit free activated halogen compounds into the ecosystem thanks to their one or more nitrogen-halogen disulfide connections. In aqueous conditions, the oxidizing halogen enables the transportation of active components to biological target sites either through fragmentation or directly to the free halogen. A microbial cell's metabolism is slowed or stopped altogether by these reactive free halogens.

Polysiloxanes

The rectilinear polymerization of polysiloxanes (a silicon oxide), is another major type of polymers. High antimicrobial property against Staphylococcus aureus and Escherichia was found in study involving the synthesis of stochastic and block siloxane biopolymers with ammonium salt quaternary unit as lateral compound by Ibemesi and Meier [7]. Statistical bloc types and composite polymers both showed the same levels of activity.

p-Hydroxy Benzoate Esters, Benzoic Acid, and Phenol

Some common disinfectants and preservatives include p-hydroxy benzoate esters, benzoic acid, and phenol. There is evidence that these monomers have antimicrobial properties. There have been attempts to increase the effectiveness of existing antibacterial agents by synthesizing new antibacterial polymers and inserting them into a polymer backbone. Research comparing p-2-propen oxyphenol and p-hydroxyphenyl acrylate to allyl p-hydroxyphenyl acetate found that p-hydroxyphenyl acrylate was the most effective antibacterial agent against bacteria and fungi. The antimicrobial activity of the p-hydroxyphenyl acrylate derivative is principally attributed to stereo electoral phenyl group effect. Antibacterial activity is enhanced in element with acryloxy or acryl groups embedded to phenyl moiety, as compared to aliphatic acrylates and hexyl acrylate. Because of its ability to kill bacteria, fungi, and algae, benzaldehyde is another crucial member of this family of chemicals. The effectiveness of benzaldehyde-containing methyl methacrylate polymers was verified against Pseudomonas aeruginosa, Dunaliella terrolecta and Bacillus macroides. Polymers are five times as efficient as acid-glass control surfaces for preventing algae growth.

Sulfonium Groups or Quaternary Phosphonium

There are similarities between the processes shown by polymers with sulfonium groups or quaternary phosphonium and those displayed by molecules having quaternary ammonium groups. Phosphonium-containing polycationic biocides outperform imidazolium salt polymers in terms of antibacterial activity. Antimicrobial activity in the water-soluble methacryloyloxyethyl trialkyl phosphonium and thermosensitive polymer NIPAAm chlorides was shown to increase with both alkyl chain length and phosphonium unit count, according to the results of a recent study.

Triclosan

Triclosan is one of the most popular antimicrobials in use today. Experiments were done where triclosan solutions were combined with a styrene-acrylate emulsion based on water, and the resulting systems were evaluated against Enterococcus faecalis. Agar diffusion tests showed that triclosan release is solvent dependent, being negligible or sluggish with water and fast with n-heptane. Triclosan was also integrated into water-dispersible PVA nanoparticles in a separate experiment, and these particles demonstrated much higher antibacterial activity against Corynebacterium compared to the aqueous/organic triclosan solutions.

5-Chloro 8-hydroxy-quinoline

The hydrolytic acrylate polymer behaviour compressing 5-chloro 8-hydroxy-quinolines was investigated at neutral, basic, and acidic pH. Hydrolysis is an autocatalytic process that may be accelerated by increasing the temperatures, the concentration of hydrophilic polymers, or both. Hydrolysis is slowed by polycondensation with N-vinyl pyrrolidone owing to hydrophobic interactions.

Peptides

Lysine (K) was used as a hydrophilic amino acid, whereas leucine (L), phenylalanine (F), and alanine (A) were employed as the hydrophobics, in ring-entrance amino acid polymerization of an N-carboxyanhydride (NCA) to synthesis different peptides. They found five series of copeptides when they changed the percentage of hydrophobic amino acids from 0% to 100%, including P(KF), P(KA), P(KL), P(KFL), and P(KAL). The P(KF) copeptides exhibit more potent antibacterial action and a wider spectrum of sensitivity compared to the P(KA) and P(KL) series, as shown by measurement of MIC figures over Serratia marcescens, Escherichia coli, Candida albicans, and Pseudomonas aeruginosa. The P(KFL) series is increasingly contrasted to P(KAL) series in the same way.

Organometallic Polymers

Metals are bound to the polymers via bond-to-carbon, synchronized bond-to-component with free bonds and pairs of electrons to other components; these metals may be found in the pendant groups or the backbone chains. Acyclovir was used as a building block in the synthesis of organotin polyamine ethers by Carraher et al. [8]. Varicella zosters viruses and Herpes simplex virus-1 (HSV-1) were used to evaluate a number of manufactured compounds with various alkyl groups (methyl, butyl, ethyl, octyl, phenyl) (VZV) and cyclohexyl. Both DNA and RNA viruses are effectively blocked by these polymers.

Polymeric Nanosized Antimicrobials

Long-lasting antimicrobial action may be achieved using polymeric nanosized antimicrobial agents since they are non-volatile and chemically stabilized, can attach to a domain of interest, and barely penetrate cellular membrane like the skin.

Polycationic antimicrobials are unique because their high surface concentration of active groups may boost their antimicrobial efficacy. Antimicrobial activities over Gram-positive and –negative micro-organisms are pooled by quaternary ammonium chemical compounds. Whenever quaternary ammonium polyethylenimines (QPEI) [9] are mixed into different polymeric matrices, they become very efficient antibacterial nanoparticles, killing a wide variety of bacteria. Biocompatibility, adaptability, and the capacity to specifically target biofilm pathogens are all selling points for lipid nanomaterials.

Polycationic Nanoparticles

There is no other kind of NM that can produce an intracellular death signal as QPEI does. Cells in biofilm layers that are not touching the nanoparticles may still be killed by some unknown signal. This finding, that NM may cause programmed cell death in bacteria, is fascinating. If these signals can be isolated, it is possible that they might be exploited to increase the NM's performance. One of the principle antibiotics limitations is their incapability to infiltrate biofilms, and such signals may be an efficient solution to this problem. The significance of PCD (programmed cell death) in bacterial cultures is not well understood, but there is mounting evidence that PCD is controlled by secreted signals and that it plays an essential part in the life cycle of bacterial strains.

Chitosan

Antibiotic resistance in bacteria is a key hazard to public health, hence developing new treatments for bacterial infections is urgently needed. **Table 1** lists some instances of microorganisms that are sensitive to chitosan, chitosan compounds, and chitooligosaccharides. These microorganisms include bacteria, filamentous fungus, and yeast. Bacteria are able to develop again after the chitosan polymer is no longer present in the growing medium, suggesting that the polymer has a growth-inhibitory effect. This is significant because chitosan-resistant cell populations may develop otherwise.

Table 1. Antifungal and Antimicrobial Chitosan Activity

Systems	Target	Inhibitions
Chitosan	Aeromonas hydrophila; Flavobacterium columnare; Edwardsiella ictalurid	Full 0.8% (A. H); 0.4% (E I, F C)
Chitosan	Candida albicans Gram-negative bacteria (Vibrio cholera, Enterobacter aerogenes, Pseudomonas aeruginosa, Salmonella typhimurium Vibrio parahaemolyticus, Pseudomonas fluorescens, and E. coli) Gram-positive microorganisms (Lactobacillus bulgaricus, Lactobacillus brevis, Listeria monocytogenes, Lactobacillus plantaru, Bacillus megaterium, Bacillus cereus, and S. aureus)	Safer and stronger effect
N-acetyl-D-glucosamine; Carboxymethyl chitosan; Chitosan hydrochloride; Chitosan oligosaccharide	C. albicans, Candida krusei, C. glabrata	Strong effects: Chitosan hydrochloride. No effects: N-acetyl D-glucosamine, and chitosan oligosaccharide. Weaker effects: Carbon-xymethyl chitosan.
Chitosan wound dressing	P. aeruginosa, L. monocytogenes, B. cereus,	Strong effects: Treatments of wounds because they are antibacterial, promotes rapid wound constriction and healing, stop bleeding, and relieve pain.
Chitosan sponge	E. coli, S. aureus	-
Chitosan nanoparticles and microparticles	E. coli, S. enterica, Vibrio cholerae, Streptococcus uberis, S. enterica, S. uberis, K. pneumonia, V. cholerae, S. aureus, S. typhimurium, Salmonella choleraesuis	Strong effects

As chitosan becomes insoluble in solutions with a pH greater than 6.5, chitooligosaccharides, which are soluble in water, are being considered as polycationic biocides. Other soluble derivatives of chitosan with antibacterial action that also avoid acidic environments include N-trimethyl chitosan, N-diethylmethyl chitosan, 2,6-diamino chitosan and sulphated chitosan. The food, textile, and cosmetic industries are just a few of the many that might benefit from this

antibacterial action. Therefore, because chitosan can generate shift bases, scientists have been able to create novel chitosan derivatives with heterocyclic moieties such the furanyl and pyrazole ring, thiophenyl or pyridyl groups. While these chitosan derivatives do not show a high level of solubility in an aqueous condition, they outperform their parent chitosan when it comes to killing gram-positive microorganisms.

There is still some debate over the mechanism by which polymers like chitooligosaccharides, chitosan, and their derivatives exert their antibacterial action. This is because there is a lack of standardization in the industry with regards to polymer characterisation, purity concerns, the employment of various microorganisms, and experimental procedures. Some research suggests that a polymer coat on the surface of cells prevents the cells from absorbing nutrients. The outer membranes of bacteria are able to connect with chitosan chains because of the presence of -NH2 groups that engage with the -COO- groups. Hence, the degree of acetylation determines the antibacterial action. Adsorption of chitosan with bacterial DNA has been postulated to prevent chitosan from penetrating cells and inhibiting RNA transcription. It's probable that a combination of processes and events contribute to the suppression of cell development.

Mw, acetylation level, polymer viscosity, and polymer concentration are all intrinsic polymer properties that influence chitosan's antibacterial effectiveness. How the polymer reacts depends on the solvent utilized to dissolve it. Citric acid, Acetic acid, and buffers like AcOH-NaAc, all of which are often used to dissolve chitosan, have been shown to have some inherent antibacterial activity (unpublished results). The examined microorganism, the growing medium, the pH, the temperatures, the ionic strength, and the physiological condition of the cells all have significant effects on the antibacterial activity.

Size of the polymer has an uncertain impact. Chitosan's antibacterial effectiveness may increase with polymer size, according to some research; nevertheless, oligosaccharides have been shown to have weaker antimicrobial action. Antimicrobial activity was shown to be highest among chitooligosaccharides with the highest DP. Chemically generated chitooligosaccharides of 2200 Da were found to have no antibacterial effect and to instead accelerate the development of E. coli by Tokura and colleagues, whereas a sample of 9300 Da was shown to suppress bacterial growth. N onetheless, other research has shown that a sample of chitosan with a minimum molecule weight of approximately 55 kDa is more effective in inhibiting microbial growth compared to a sample with a maximum molecule weight of approximately 155 kDa. In a separate experiment, researchers found that variations in medium pH led to distinctive patterns. The antibacterial activity was shown to be higher at higher MW under acidic pH settings. Antimicrobial activities, nonetheless, enhanced with low MW at neutralized pH. Nevertheless, no generalizations have been made on how chitosan Mw affects antibacterial activity. There seems to be a correlation between the degree of acetylation and antibacterial efficacy.

Antibacterial, antifungal and antiviral properties have been shown in chitosan (Ch) nanoparticles. Recently, Chitosan-hydroxycinnamic acid conjugates with potent antimicrobial activity have been developed. Ch's biocompatibility, nontoxicity, antibacterial capabilities, low immunogenicity, and absorption-enhancing abilities are largely responsible for its extensive use. N-acetylglucosamine polymer chitin’s N-deacetylation [10], which is present in insect exoskeletons, yields nanoparticles known as chitosan NM. The antibacterial activities of the chitosan nanomaterials is dependent on pH and is also solvent. Chitosan inhibited the effectiveness of metal NM, namely Zn. Hence, it shows that antibiotics are a better combination than metal NM.

It is unclear how chitosan exerts its antibacterial effects. Chitosan inhibited various membrane-related processes in B. cenocepacia, according to a recent in-depth research. They included respiration, resistance nodulation division (RND), drug efflux transportation and mechanism. Possible causes include the instability of membrane protein s and membrane lysis resulting from the combination of lipopolysaccharides with chitosan. Nevertheless, it appears that many questions remain unanswered about how NM really works. There are still many undiscovered methods of killing NM that need to be investigated. It is currently unclear how NM's therapy combinations affect patients. Finally, it is important to clarify the role of the intrinsic mechanisms of programmed cell death in bacteria, which have been the subject of debate, in NM-dependent killing.

V. CONCLUSION

New bactericidal materials are needed since bacteria strain-resistant to the present antibiotics have become a prevailing concern of public health. As a result, there is a pressing need for the discovery of cutting-edge approaches and materials to address these critical problems. Several novel antimicrobials have been made possible by the development of nanotechnology. Because of its compact size, the NM is well suited for performing antimicrobial biological procedures. Nanoparticles of various forms, including those made of metals and organic compounds have shown great promise as bactericidal and fungicidal agents, suggesting that they may serve as effective antibiotic reagents in the treatment of wounds and similar medical problems. Size, shape, and concentration are just a few of the features that may affect how effective these nanoparticles are. In addition, the characteristics of such substances are affected by the atomic abundance of the particles' surfaces. The ratio of surface atoms to total atoms rises with decreasing particle size, increasing the intensity of the reaction. Several types of NM have been shown to have antibacterial action against different microorganisms. Likewise, including NM into scaffold materials has been met with appropriate biocompatibility. The use of nanomaterials as a foundation for developing novel approaches to combating bacterial infections is currently being explored.

Data Availability
No data was used to support this study.

Conflicts of Interests
The author(s) declare(s) that they have no conflicts of interest.

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