REVIEW ARTICLE

Nanomaterials as Multifunctional Antibacterial Agents: Mechanisms, Applications, and Challenges in the Era of Antimicrobial Resistance

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ABSTRACT

The development of antimicrobial resistance, often known as AMR, poses a huge threat to the health of people all over the world around the globe. It is possible that the current death rate may exceed 10 million per year by the year 2050. It is necessary to find new solutions since antibiotic resistance is increasing as a result of a number of causes, including biofilms, efflux mechanisms, and bacteria that are resistant to several drugs. Nanomaterials, and silver nanoparticles in particular, have emerged as powerful antibacterial agents with a variety of modes of action. These mechanisms include membrane permeabilization, formation of reactive oxygen species (ROS), directed cell targeting, and disintegration of biofilms. Some of the kinds of nanomaterials that are investigated in detail here include metal oxides, carbon-based structures, polymers, and hybrids. Additionally, the physicochemical properties that influence the antibacterial activity of these nanomaterials are also thoroughly investigated.
Among other applications, it examines their potential for coordinated antibiotic delivery and their reactivity to external stimuli in the medical, dental, and orthopaedic domains. Toxicology, scalability, regulatory gaps, resistance risks, and safe clinical use of the medicine are all thoroughly examined, along with other translational issues. To make nanotechnology fulfill its potential in combating the AMR epidemic while simultaneously considering biosafety and environmental concerns, this paper compiles previous accomplishments to provide design principles and research goals.

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INTRODUCTION

A major global health concern is antimicrobial resistance (AMR). By 2050, it may be costing billions of dollars in lost productivity and causing up to 10 million deaths annually if current trends continue [1-3]. We are entering a "post-antibiotic era" when conventional treatments are losing their efficacy due to the rapid emergence of multidrug-resistant bacterial strains caused by the excessive and inappropriate use of antibiotics. Worse still, progress in discovering new antibiotics has been sluggish, with just a handful of candidates identified since the turn of the millennium. Because of resistance, many of these medications are already useless. Poisoning, allergic reactions, and ineffectiveness against biofilms, groups of bacteria that shield pathogens from treatment, are additional issues with conventional antibiotics [3,4]. Due to their vast surface area and diverse interactions with bacterial cells, among other unique physical and chemical properties, nanomaterials are gaining attention as potential next-generation antibacterial treatments [5-7]. Nanomaterials regain their antibacterial efficacy due to these characteristics, which improve drug delivery, optimize pharmacokinetics, and penetrate biofilms [2, 4]. Nanoparticles made of metals, such as zinc oxide, gold, or silver, may cause DNA damage, produce reactive oxygen species, and rupture cell membranes [5]. Because of their antimicrobial properties, these nanoparticles work wonders against bacteria.

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Several nanoparticles with antibacterial properties have been identified, and they do not depend on resistance mechanisms [8]. These nanoparticles are used to forestall the development of resistance. Research into nanoparticles' antibacterial processes aims to fill gaps in our understanding by shedding light on their capacity to circumvent resistance barriers and their roles in the effective delivery of drugs. There has been much research into nanomaterials with the hope that they may one day serve as adjuncts or substitutes for antibiotics in a variety of therapeutic and clinical settings. Also explored is the possibility that they might aid in the treatment of disorders that have shown resistant to many medications. Furthermore, we thoroughly examine the difficulties linked to clinical translation. The potential for resistance to develop, limitations on scalability, and worries about the treatment's safety are all obstacles. The study's overarching goal is to provide recommendations for the development of future nanomaterials and strategies for their efficient use in therapeutic contexts. By incorporating prior research, these suggestions will be realized. The safety of nanoparticles for use in medicine depends on their having undergone extensive testing and evaluation by regulatory bodies.

This is done in order to evaluate their cytotoxicity and safety profiles. A significant amount of promise lies within nanomaterials.

As a result of the fact that nanoparticles may unwittingly increase the development of resistance in some circumstances, the need of careful design, continuing monitoring, and responsible use of these innovative antibacterial treatments is further highlighted.

OVERVIEW OF ANTIBACTERIAL NANOMATERIALS

The chemical composition of antibacterial nanoparticles is the major factor that determines these particles' classification. Every single one of them fights germs that are resistant to antibiotics in their own unique manner. There are a broad number of methods in which nanoparticles composed of metals or metal oxides, such as titanium dioxide, silver, gold, copper, zinc oxide, or other substances of a similar kind, have the potential to eliminate germs [9–11]. The reason for this is because they have the ability to break down the cell walls of bacteria and release reactive oxygen species. Carbon-based structures, including as graphene derivatives, fullerenes, carbon nanotubes, and carbon dots, have the ability to generate physical damage and oxidative stress [12]. This is because these structures have a large surface area and powerful mechanical characteristics. When metals are combined with carbon or polymers, hybrid composites are created. These hybrid composites have synergistic effects that boost their performance and avoid the formation of resistance [13, 14]. Nanostructures made of dendritic and polymeric materials provide biocompatible platforms for the delivery of drugs in a specific manner. It is conceivable to fine-tune the antibacterial activity of these nanoparticles by changing their physicochemical properties. This is a possibility. Chemical changes are responsible for determining the stability and specificity of particles, surface charge is responsible for governing the interaction with membranes, and the shape and size of particles are responsible for determining cellular uptake [15, 16]. The regulated dissolution, ion release kinetics, and colloidal stability are the factors that make it feasible for the substance to maintain its activity in biological environments. At the same time, stimuli-responsive "smart" designs enable regulated agent deployment in response to temperature, light, or pH stimuli [9–11]. This helps to reduce the amount of collateral damage that occurs. Ensuring the safety of clinical translation requires addressing many issues. This class includes considerations such as cytotoxicity, environmental impacts, resistance potential, and changing regulatory needs. Clinical translation safety necessitates the creation of novel protocols and the implementation of rigorous safety testing, notwithstanding the possible advantages of these approaches.

MECHANISMS OF ANTIBACTERIAL ACTION

According to studies done by Khalifa et al. [17] and Khaksar [18], AgNPs may serve several purposes, one of which is acting as an efficient antibacterial agent. Their objective is accomplished when they come into touch with bacterial membranes by use of electrostatic forces. Because of the harm it takes in from this contact, the membrane's porosity may be slowly but surely increasing. Nanoparticles' large surface area relative to their volume makes it feasible for them to cling to and penetrate bacterial cell walls. The findings of Gunawan et al. [20] and Morones-Ramirez et al. [19] demonstrate that silver nanoparticles have a wide range of action against Gram-positive and Gram-negative bacteria.

It has been shown by the writers of the papers listed earlier. By increasing the permeability of Gram-negative bacteria's membranes or by destroying the peptidoglycan layer of Gram-positive bacteria, they may cause substantial harm to bacterial cells. Bacterial cell death involves both of these processes. The antibacterial activity of AgNPs is determined by the way these nanoparticles produce reactive oxygen and nitrogen species (ROS and RNS), according to Gunawan et al. [20], Merghni et al. [21], and Fanoro and Oluwafemi [22]. As antimicrobials, AgNPs are useful. Important cellular components like DNA, lipids, and proteins are damaged when oxidative stress develops. Silver ions, released into the environment by AgNPs, may trigger a cascade of reactions that aren't all oxidative. The silver ions are capable of producing these kinds of reactions. Some examples of such processes include protein misfolding and enzyme deactivation. This modifies the metabolic processes of bacteria, which in turn increases the efficacy of their antibacterial properties. According to Fanoro and Oluwafemi [22], upon their entry into bacterial cells and interactions with nucleic acids and ribosomes, silver nanoparticles (AgNPs) are thought to induce DNA damage and a slowdown in the replication and transcription rates. Based on their results, the researchers described earlier came to this conclusion. To evade the harmful effects of medications and immune reactions, biofilm development is a crucial defense mechanism. According to Xing et al. [15], AgNPs may efficiently stop bacteria from sticking to surfaces, which stops them from forming biofilms. Further evidence that AgNPs disrupt preexisting biofilms and alter quorum sensing—a critical bacterial communication mechanism for biofilm formation, is provided by themselves.

Because of this, the therapeutic therapy that is being administered against microorganisms is more successful than it was before. Silver nanoparticles (AgNPs) have a great deal of antibacterial properties; however, there are a lot of people who are concerned that they might be harmful to human cells, that they might have an effect on the environment, and that they might cause bacteria to develop resistance to nanoparticles. This is despite the fact that they have a lot of antibacterial properties. In order to effectively combat antibiotic resistance, it is imperative that future research concentrate on perfecting the formulations of nanoparticles in such a way that they are both safe and effective. Because of this, the issue will be able to be treated in a more efficient manner.

NANOMATERIALS AND ANTIMICROBIAL RESISTANCE

Patients throughout the world face the challenge of antimicrobial resistance (AMR), but there are a number of strategies that have proven successful in this fight. The application of nanoparticles is one such method. These molecules may be able to increase the effectiveness of currently used antibiotics, decrease the probability that resistance will develop in the future, and even avoid the usual routes that lead to resistance. However, the prospective effects of its continued usage are unclear at this time. In this reply, we look at the prospect that nanoparticles could be able to defeat processes that have developed resistance to antimicrobials. Furthermore, this answer delves into the possible hazards of nanoparticle usage and the synergistic effects of nanoparticles with existing antimicrobials. Nanomaterials may enter cells and interfere with their functions without being eliminated or destroyed by defense enzymes, as shown by Gao and Zhang [23] and Ndayishimiye et al. [24]. It was shown by the nanomaterials. This is now within reach because to the unique physicochemical characteristics of nanoparticles.

It is possible to avoid the common mechanisms of bacterial resistance by doing so. These processes include efflux pumps, enzymatic degradation, and changes in target site. nanoparticles have been shown to be effective in the battle against persister cells, multidrug-resistant cells (MDR), and extensively drug-resistant cells (XDR), according to research that was carried out by Rotello [25]. These nanoparticles target populations that are notoriously resistant to treatment by breaking down biofilms and gaining access to cells. These are the two strategies that they employ to do this. Research carried out by Khan [26], Zhao et al. [27], and Alamgir and Haider [28] reveals that nanomaterials have the potential to be used as nanocarriers and conjugates of antibiotics. These findings were presented in the previous sentence.

The concentration of medications at infection sites is made possible as a result of this, which results in improved local dosing and a reduction in systemic exposure. Synergistic effects are produced via co-delivery strategies, which result in increased binding affinity and effectiveness against germs that are resistant to the drug.

According to Xie et al. [8] and Munir and Ahmad [29], nanomaterials have the potential to be beneficial; yet, they also pose a risk of bacterial adaptive responses and tolerance and hold the potential for such development. In light of the fact that there is a lack of information about the long-term consequences of these dangers for evolution, it will be essential to carry out extensive research and monitoring in order to ensure that these materials will continue to be effective in alleviating the problem of antimicrobial resistance.

MULTIFUNCTIONAL NANOPLATFORMS

The use of multifunctional nanoplatforms as a possible weapon in the battle against antimicrobial resistance (AMR) is gaining a lot of interest. These nanoplatforms may prove to be an invaluable tool due to their dual diagnostic and therapeutic capabilities. By reducing their negative side effects, these platforms increase the effectiveness of antimicrobial therapy. Using the unique characteristics of nanomaterials allows this to be achieved.

Because they provide unique techniques to recognizing, isolating, and removing hazardous bacteria, the development of such systems is necessary at a time when antibiotic resistance is developing. This is because these systems give novel approaches. In the parts that are to come, we will talk about several components of multifunctional nanoplatforms. These components will include theranostic systems, combination modalities, and targeting techniques. One area of research and development that is constantly expanding is the creation of multifunctional nanomaterials that include dual antibacterial characteristics as well as imaging or sensing capabilities. The diagnosis and treatment of bacterial infections in real time is made possible as a result of this situation [30]. Imaging is one of the applications that may be performed on these nanoplatforms, which can also be loaded with antimicrobial agents in the form of nanoparticles. Consequently, this not only enhances the precision with which medication is administered, but it also has the ability to avoid resistance by preventing the drug from reaching places that are not intended to receive it [31, 32]. This theory serves as the foundation for the idea of antibacterial systems that are in response to stimuli. Only when they detect a change in environmental elements such as light, magnetic fields, pH, or enzyme activity do they produce medicine. This is the only time they perform this function. Because of this, the antibacterial activity is prevented from spreading beyond the location of infection, which in turn causes damage to healthy tissues. One example is the photodynamic therapy, which may be accomplished by the use of platforms that are triggered by light. The use of this technique results in the production of reactive oxygen species, which are very effective in eliminating bacteria. There is a therapeutic alternative that is both highly focused and easily controllable [27]. Researchers are developing photothermal and photodynamic antibacterial nanomaterials as integrated, synergistic platforms that use heat induced by photothermal therapy in conjunction with reactive oxygen species produced by photodynamic technology. The goal of these nanomaterials is to eradicate bacteria, including those that are resistant to multiple drugs and those that are found in biofilms. It is possible that these approaches might sidestep many of the problems that are associated with traditional antibiotics [33, 34]. This is accomplished by simultaneously damaging bacterial membranes via the use of heat and oxidation, as well as breaking down protective extracellular matrix. In addition, chemodynamic nano-systems make use of catalytic nanomaterials in order to transform endogenous hydrogen peroxide into very harmful hydroxyl radicals at the precise location where the infection is taking place. Because of this, the antibacterial capabilities are enhanced to a greater degree. Multi-mechanistic platforms are created when chemodynamic therapy is combined with other therapies, such as controlled gas release or sonodynamic activation. These platforms boost the bactericidal effectiveness of the treatment and contribute to the elimination of resistance by attacking pathogens via several biochemical pathways [33, 35, 36]. Nanomaterial surfaces that have been painted with targeting ligands, antibodies, or peptides have been shown to dramatically increase selective binding to bacterial cells, according to research conducted by Kaur et al. [37] and Dai et al. [35]. This makes it possible to concentrate therapeutic drugs at infection sites while minimizing the amount of off-target dispersion and adverse effects that occur. In order to create antibacterial nanoplatforms that are more effective against bacteria and less toxic to host cells, researchers Kaur et al. and Makabenta et al. emphasize

Table 1. Key Applications of Antibacterial Nanomaterials

Application/Technology	Main Functionality	Advantages	Reference
Wound Dressings & Tissue Engineering Scaffolds	Antimicrobial protection + tissue regeneration	Sustained release, reduces post-surgical infections	[38, 39]
Dental Materials & Bone Implant Coatings	Inhibits bacterial adhesion & biofilm formation	Improves implant longevity, prevents device infections	[42]
Catheters, Stents & Indwelling Devices	Protective barrier against microbial colonization	Enhances patient safety, reduces device infections	[41]
Nanoparticle Drug Delivery Systems	Targeted antibiotic release at infection sites	Minimizes systemic toxicity, treats resistant strains	[40, 41]
Food Packaging Materials	Inhibits microbial growth, extends shelf life	Maintains hygiene, prevents contamination	[44, 46]
Water Disinfection & Surface Coatings	Broad-spectrum antimicrobial surfaces	Eco-friendly hygiene maintenance	[44, 46]
Veterinary & Agricultural Infection Control	Controls livestock/crop infections	Reduces antibiotic use, curbs AMR spread	[37, 40]

the importance of meticulous nanomaterial design, including selecting the appropriate core composition and tailoring the surface chemistry, to capitalize on the structural and physicochemical differences between bacterial and mammalian cell membranes. This is a crucial step that has to be done to ensure the safe transfer of antibacterial nanoplatforms from the lab to healthcare providers. There are still many practical hurdles that multifunctional nanoplatforms must pass before they can be effectively used, despite their hopeful future in the battle against antimicrobial resistance (AMR). Finding answers to the problems of scalability, safety, and the possibility of resistance development is necessary for the effective implementation of these technologies in healthcare settings. Integration of emerging technologies like synthetic biology and artificial intelligence into these systems is likely to pave the way for the development of more effective and tailored antimicrobial therapies [27].

APPLICATION DOMAINS

Using nanoparticles, antibacterial agents with many uses and a wide variety of potential applications were created. In the battle against antimicrobial resistance (AMR), nanomaterials have emerged as a prominent tool. Their huge surface area-to-volume ratio, capacity to break microbial membranes, and modifiable surface chemistry make them useful against bacteria that have evolved resistance to a variety of medications.

The many applications of nanoparticles are studied in this area, with a specific focus on the use of nanoparticles in the disciplines of healthcare, dentistry, orthopedics, and non-clinical applications.

The adaptability and efficacy of nanoparticles in the fight against infection have led to a surge in their use in the domains of dentistry and medicine. In order to give antibacterial and wound-healing qualities that are long-lasting, nanoparticles have been used in tissue engineering scaffolds and wound dressings. These nanoparticles include silver and copper for example. It is possible that the application of coatings of a similar kind to implants might lessen the probability of postoperative infections [38, 39]. Concurrently, the development of medication delivery systems that are based on nanoparticles is taking place with the intention of controlling infections on both a local and a systemic level. The targeted release of antimicrobial drugs at the site of infection is made possible by these approaches, which is particularly beneficial for the treatment of bacterial strains that are resistant to treatment [40, 41]. These strategies not only reduce the likelihood of systemic toxicity and off-target effects, but they also enhance the efficacy of antimicrobial therapy. Nanomaterials are an important component in the fields of dentistry and orthopedics because they provide different approaches to the prevention of infections that are linked with medical equipment. This is the reason why nanomaterials are considered to be an essential component. The researchers Sui et al. [42] and Handy et al. [43] discovered that the application of nanocoatings to dental materials and bone implants reduced the development of biofilms and the attachment of germs to the regions that were impacted. The implants will have a longer lifespan as a result of this, and the likelihood of their being infected will also be reduced. For the purpose of constructing barriers that prevent microbial colonization and infections, researchers Salmani-Zarchi et al. [41] and Handy et al. [43] have focused their attention on the application of nanomaterial coatings to indwelling medical devices. These devices include stents and catheters. The goal is to make patients safer while also improving the therapeutic results. Nanoparticles are helping in many different areas of the fight against antimicrobial resistance (AMR), not just in dentistry and medicine where they have several useful applications. It is possible to include them into packaging materials to inhibit the development of microorganisms and prolong the food's shelf life, as proposed by Galhano et al. [44] and Ali [45].

This would be done in order to improve the shelf life of food. Using these compounds in water disinfection systems and applying antimicrobial surface coatings are both viable approaches to further enhance cleanliness and minimize the danger of contamination. Both of these methods have the potential to provide further benefits. In both veterinary and agricultural contexts, Kee et al. [40] and Kaur et al. [37] highlight the use of nanomaterials for the purpose of disease control in livestock and crops.

This is accomplished by lowering the dependence on conventional antibiotics and assisting in the mitigation of the development and spread of antimicrobial resistance. Nanotechnology has the ability to protect the health of humans, animals, and the environment, as shown by the many uses already in existence. There is a comprehensive list of all the medicinal and non-clinical uses of nanoparticles that can be found in Table 1. Additionally, it illustrates the tremendous usefulness that they possess in the fight against antibiotic resistance.

The implementation of nanomaterials is not always a walk in the park, despite the fact that they might be advantageous in a variety of settings. In the long term, it is necessary to address concerns about the biosafety, possible toxicity, and environmental implications of nanomaterials. There is nevertheless cause for worry over the emergence of microbes that are resistant to nanomaterials, despite the fact that this kind of resistance is less prevalent than antibiotic resistance. For this reason, it is imperative that these issues be carefully studied, and that suitable laws be developed, in order to ensure that nanomaterials are used in a manner that is both safe and effective in the fight against antimicrobial resistance [43, 47].

SAFETY, TOXICOLOGY, AND ENVIRONMENTAL CONCERNS

Nanoparticles have the ability to disturb the human microbiota and have a detrimental impact on mammalian cells; the rate at which they are harmful is depending on the dosage that they are administered. Due to the fact that they have a large surface area despite their tiny size, they are able to easily interact with cell membranes, which may lead to oxidative stress and damage to cells. Cationic nanoparticles, on the other hand, prefer to interact directly with cell membranes [48, 49]. This is in contrast to anionic nanoparticles, which have a tendency to accumulate in lysosomes and promote inflammation. On top of that, nanoparticles (NPs) possess immunomodulatory characteristics, which means that they have the capacity to either cause positive or negative results.

Immune cell activation, altered cytokine production, the development of reactive oxygen species (ROS), and the building of a protein corona on nanoparticles are all potential causes of inflammation [49, 50]. In spite of this, it has been established that PEGylation and other surface modifications may substantially reduce immunogenic effects by increasing the length of circulation and decreasing inflammatory pathways [51]. The fact that nanoparticles have a tendency to accumulate in ecosystems, where the production of reactive oxygen species (ROS) disrupts microbial communities and changes ecological equilibrium, is a major concern regarding the environmental impact of nanoparticles, according to Oberdorster [52], Elbehiry and Ali et al. [38, 46], and other researchers. This is a major concern. It is essential to have a solid understanding of the mechanisms of biodegradation as well as the potential dangers of bioaccumulation in order to accurately estimate their lives. As Patel et al. [53], Oberdorster [52], and Adhikary et al. [54] have pointed out, regulatory toxicology frameworks that include standardized toxicity testing and risk assessment methodologies are required in order to prevent widespread dangers that are brought about by the rapid commercialization of nanotechnology. It will be vital for legislators, toxicologists, and engineers to work together across disciplines in order to guarantee that developing technologies do not pose a threat to the health of humans or the environment.

It has been shown by Shoukani et al. [51] and Singla et al. [55] that the core composition, size, shape, and surface charge of nanoparticles have a substantial influence on the efficacy of the nanoparticles as well as the potential toxicity of the nanoparticles. It is now possible to give predicted toxicity assessment using machine learning and QSAR algorithms. This is done in order to suggest safer formulations. There are surface engineering techniques that have been suggested by Shoukani et al. [51] and Ali et al. [46] to raise the therapeutic index while simultaneously lowering off-target effects. One example of such an approach is cell membrane-mimetic coatings. These coatings improve the biocompatibility, target specificity, and overall safety profiles of medications that are intended for clinical use. The antibacterial potential of nanomaterials must be fully realized, but first we must guarantee that they are safe for both people and the environment. This may be accomplished via the use of new design approaches and the integration of toxicological assessment.

TRANSLATIONAL AND REGULATORY CHALLENGES

The authors Liu and Meng [56] and Đorđević et al. [57] have brought attention to the significant difficulties that arise when attempting to transition nanomaterial fabrication from laboratories to factories. In order to ensure the reliability of therapeutic efficacy and safety, it is necessary to keep nanoparticle size, shape, and surface features at a consistent level. Microfluidics and iterative process optimization are two examples of new techniques that are showing promise. However, new approaches are showing promise. Because variances might have an effect on clinical findings, it is essential to manage the variability that occurs from batch to batch. In order to ensure that the output is consistent, it is vital to use production methods that are standardized and quality control systems that are severe. It is equally important to have comprehensive characterisation criteria that encompass physical, chemical, and biological research in order to guarantee that nanomaterials will consistently fulfill high safety and effectiveness requirements prior to their use in clinical settings. In a study conducted by Arrazuria et al. [58], the researchers found that the decision between using in vivo or in vitro models had a substantial influence on the efficiency of antibacterial nanoparticles in real-world situations. On the other hand, in vitro models make it feasible to undertake fundamental mechanistic research, and in vivo models demonstrate the complex interactions that take place between different species. There are a number of variations in models, such as murine pneumonia, which bring to light the need of standardized protocols in order to improve clinical relevance. Furthermore, as Elbehiry and Abalkhail [38] have pointed out, the clinical trial pipeline for nanomaterials is still in the basic phases even though they have been introduced. The findings of the continuous examinations of their safety and efficacy will be the decisive factor in evaluating whether or not they have the potential to be used in therapeutic applications that are practicable in the future. In accordance with the findings of Đorđević et al. [57], the regulatory framework for nanomaterials is distinguished by its dynamic nature and the lack of a clearly defined direction. In order to guarantee that research pipelines are aligned with current needs and that safe clinical translation is hastened, it is necessary to initiate interaction with oversight organizations well in advance of the process and to maintain this interaction throughout the whole process. Important ethical concerns include the establishment of public confidence in the use of nanomaterials, the mitigation of cytotoxicity and environmental problems, and the assessment of the potential dangers and advantages of the usage of nanomaterials. Khalifa et al. [17] and Chauhan et al. [59] are the ones who have brought these challenges to light, respectively. It will need collaboration between researchers, manufacturers, and regulators to address the translational, safety, and regulatory challenges that these antibacterial drugs face before they may be utilized therapeutically to combat antibiotic resistance. Because of this, they will be able to defeat the antibiotic resistance problem.

CONCLUSION AND FUTURE PERSPECTIVES

With the development of antibiotic resistance, there is an immediate need to find new antimicrobial drugs, and nanotechnology is playing a larger and larger role in this search. Nanotechnology is becoming more and more crucial to this pursuit and is helping to bolster it. In addition to producing reactive oxygen species and allowing for the targeted delivery of medication, nanomaterials may break bacterial membranes in a way that is different from the normal approaches. This explains their efficacy against biofilms and bacteria that have evolved a resistance to their original medicinal targets. The multifunctional features of these antibiotics allow them to sidestep the problems often associated with traditional antibiotics. Such properties include, but are not limited to, the capacity to penetrate biofilms, to work in tandem with other treatments, and to exhibit bactericidal effects either alone or in reaction to light. Combining nanotechnology with state-of-the-art diagnostics, AI, and personalized treatment plans has the potential to improve the accuracy and efficiency of antibacterial medicines.

This will allow for the treatment of bacterial infections. For the purpose of ensuring that these laboratory discoveries are successfully implemented in clinical settings, it is vital to address problems of safety, scalability, regulation, and collaboration across different fields of study. There is a great lot of anticipation that nanotechnology will bring about a revolution in the treatment of antibiotics and contribute to the decrease of the pandemic of antibiotic resistance that is common all over the globe. This is because nanotechnology has the potential to bring about a revolution in that treatment. This has been done by a mix of constant research and the efforts of several people working together.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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