

The Role of Nanotechnology in Microbiology: A Scientific Revolution in Antimicrobial Treatments

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Abstract

This work discusses the relationship between microbiology and nanotechnology, exploring their applications and impact across various fields, including medicine, agriculture, and industry. It examines the properties and structure of nanoparticles, their effects, and the most effective antibacterial nanomaterials. The paper also discusses the general mechanisms of action of these particles, including their role in stimulating ion release, oxidative and non-oxidative processes, and their intracellular functions, specifically their ability to inhibit, kill, or limit bacterial growth. Furthermore, it addresses the advantages and disadvantages of nanoparticles, despite promising results in many recent studies, and the potential concerns arising from their use in diverse fields and their environmental impact. Despite the excessive costs involved, the development of nanotechnology and nanoengineering points to a promising future. In addition, the effectiveness of alternative and natural treatments such as honey and essential oils, and the integration of nanoparticles with them to increase their effectiveness and biological activity to eliminate disease-causing bacteria, will be discussed.

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1. Introduction

One of the advantages of nanomaterials is that they have a single size ranging from 1 to 100 nanometers. For this reason, they possess unique physical and chemical properties that make them distinct and different from their counterparts [1]. Their nanoscale size is responsible for the increase in surface area and is an important factor in adhesion to the cell surface and penetration [2-3]. Therefore, combining nanotechnology with microbiology produces unique materials with multiple applications in various fields such as medicine, microbiology, and other scientific disciplines [4]. Previous studies have shown promising and interesting results in combining nanotechnology with microbiology in various fields [5]. Given the importance of microbial therapy in reducing disease, it represents an attractive alternative to physical and chemical treatments. Research has been conducted on microorganisms to produce biologically active nanostructures for various uses. Nanoparticles offer a wide range of properties due to their superior characteristics and high activity. Nanomaterials, when coexisting with microorganisms (such as cells, tissues, membranes), can provide active surface advantages and risks (such as toxicity, drug delivery efficiency, and

immune response). Since the overall biological effects of nanoparticles are triggered and regulated by interactions at the biomaterial nanomaterial interface, the development of nanotechnology can greatly benefit from the ability to predict these interactions (such as size, charge, shape, surface chemical composition) based on atomic properties, especially before material formation [6]. In the case of antibacterial drugs, these substances can work by stopping or inhibiting the growth of bacteria that infect and cause disease in all living things. The average size of microorganisms is in the range of micrometers (μm) (10^{-6} meters). Genes and drugs are used as medicinal products to eliminate pathogenic bacteria or prevent their growth [7]. The widespread use of antibiotics has led to the emergence of resistant strains and further complicated the clinical problem with the spread of bacteria in epidemic form among patients [8]. On the other hand, nanomaterials exhibit promising potential thanks to their unique physical and chemical properties. Studies have proven the ability of nanomaterials to penetrate bacterial cell membranes due to the properties related to the dimensions and size of nanoparticles [9]. The action of nanoparticles against microorganisms begins by stimulating their particles and producing oxygen, which causes an oxidative stress inside the microbial cells, then penetrating them and releasing silver ions. One of the advantages of these materials is their ability to react inside living cells [10]. There is a need to address bacterial resistance resulting from the use of traditional antibiotics. Failure to address this condition causes the emergence of a number of resistant strains and may lead to the spread and resurgence of infectious diseases. Microorganisms acquire resistance to antibiotics either as a result of a new mutation within the cells or as a result of horizontal gene transfer from one microorganism to another directly. Viruses may be an intermediary for transferring genes to bacteria or due to similar factors. Therefore, there is a need to develop new strategies for producing new antibiotics and overcoming bacterial infections [11]. There are types of nanomaterials, for example, copper, gold, and silver, which are characterized by a surface area in addition to their volume. This increases their interaction against microbes. They also have the property of generating oxygen and releasing metal ions, which enables them to disrupt the metabolism of microbes and disable biofilms, proteins, and DNA. In addition, there are bimetallic nanoparticles that have enhanced effects against microbes as a result of interactions between the metals. Light and magnetic fields also increase the activity of these nanomaterials [84].

2. The Use of Nanotechnology in the Field of Medicine

The small size of nanomaterials facilitates their penetration and adhesion to bacterial cell surfaces, making them antibacterial and leading to their use in various fields [12]. Nanoengineering has further developed the use of nanoparticles, increasing their effectiveness and activity in reducing disease, eliminating infections, and achieving their targets more quickly [13]. Recent studies have classified nanomaterials as organic or inorganic and carbon-based on their structure. Substances smaller than 100 nanometers can bind to proteins, carbohydrates, and other molecules [14]. Inorganic nanoparticles, including basic metals, oxides, and carbon derivatives such as graphene, possess stability, biocompatibility, and low toxicity. Figure 1 shows some basic classifications of the nanoparticles [15]. The effectiveness of antimicrobial particles is determined by their physical and chemical properties, size, temperature, and manufacturing method [16-17]. Thanks to this property, its small size, and its ability to reach its target, it can be used in the medical field to overcome bacteria, limit their growth, and eliminate infections. This feature helps pharmaceutical companies to exploit it, market it, and produce effective and fast-acting drugs [18-19]. Some external factors, such as light and heat, can increase the activity of nanoparticles, driving them to reach their target directly. This makes them easily accessible to cancerous tumors via the bloodstream, giving them a promising future. As for smart pills, they can be wirelessly controlled using sensors to determine dosage schedules. Despite these advantages, nanomedicine faces obstacles in clinical applications, including environmental impact and accumulation in living tissues and organs [22]. In addition, nanomedicine has diagnostic functions characterized by speed, accuracy, and efficiency due to its ability to diagnose even in low body fluids such as blood, urine, human tissues, cell cultures, etc. This feature enables the rapid diagnosis of infectious diseases, cancerous tumors, or genetic diseases. Among the nanobodies currently used for diagnosis are paramagnetic nanoparticles, nanocrystals, quantum dots, nanocapsules, and nanoparticles [21]. In addition, nanoparticles can be used as wound dressings as they contain metal oxides, silver ions, or hydrogels, in addition to nanofibers, which increase antimicrobial activity and aid healing through tissue regeneration. These dressings can be further developed by adding sensors that enable them to monitor wounds [85]. Nanoparticles can be utilized through their ability to deliver and release drugs sustainably, and they can be developed and made to respond to external factors, such as light, to increase their activity [86]. Nanoparticles may be used for the diagnosis of some non-surgical skin diseases or incorporated into smart wound dressings that can diagnose and identify the type of microbe [87].

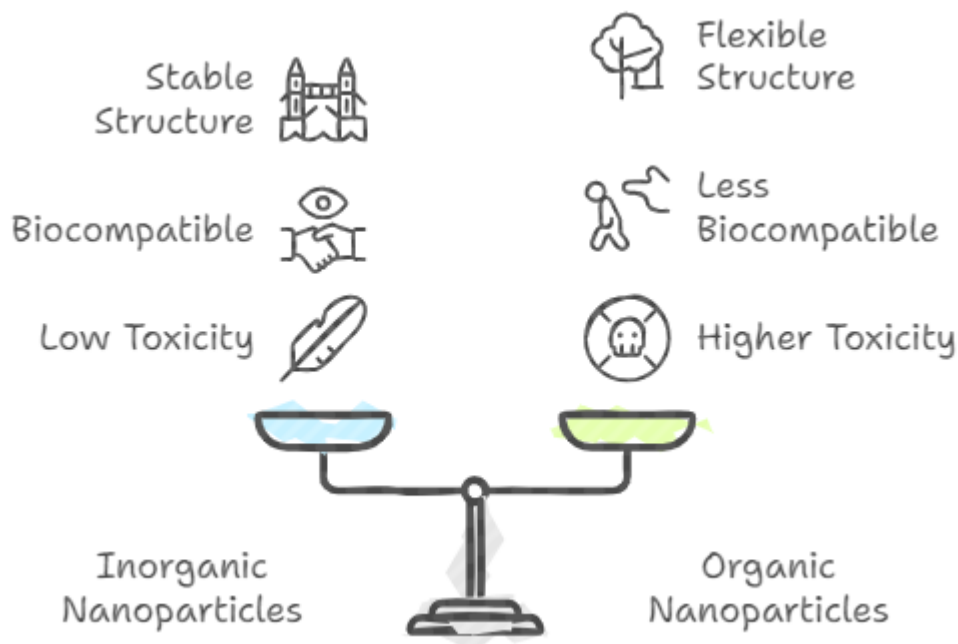


Figure 1 shows organic and inorganic nanomaterials and their effect on stability, toxicity, and biocompatibility [22].

3. Mechanism of Action of Antibiotics Resistant to Microorganisms

Hospitals are a microbe-rich environment due to the high number of illnesses and medical and surgical procedures. Although people recover and the disease is controlled, there are still those with weak immunity or who have not yet recovered. For this reason, cases of infection spread increase and may lead to death, and infections require additional costs for the health care of patients [23-24]. Microbial infection is caused by bacteria, viruses, or similar agents. Factors contributing to its severity include diarrhea, food poisoning, respiratory illnesses, skin infections, and others. Some diseases worsen and become more severe if the infection is left untreated, which is sufficient reason for their spread throughout the body and determines the severity of the infection [25-26]. If treatment is neglected and the bacteria worsen, they produce potent toxins capable of disrupting the body's systems through several factors, including inhibiting protein synthesis and cell components, damaging cell membranes, and producing endotoxins that exacerbate certain conditions, such as allergic bronchitis [27]. Treatment resistance is an old phenomenon and poses a real threat against pathogens in all areas, reducing the effectiveness of drugs and thus increasing mortality rates due to treatment failure [28-29]. Because of microbial resistance to drugs, the idea of using nanoparticles as antimicrobials emerged. The idea of using nanoparticles is due to their having properties in terms of shape, size, chemical composition, concentration, and others. In addition, many particles, including silver, zinc, and titanium, have been classified as Generally Recognized As Safe (GRAS) by the US Food and Drug Administration. Therefore, their use is permitted as treatment delivery systems and even in the food industry [30, 31, 32]. Figure (2).

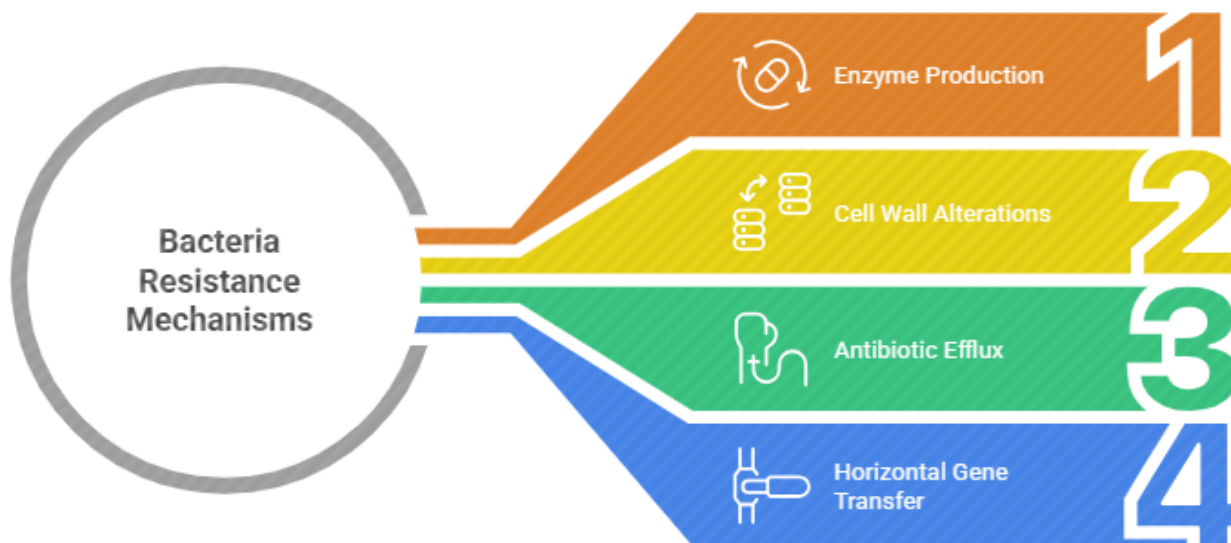


Figure 2: The cellular (Enzyme, Cell wall, Efflux) and genetic (Horizontal Gene) mechanisms of bacterial resistance to antibiotics [33].

4. Mechanisms of Nanoparticles Against Bacteria

Nanotechnology possesses qualities and characteristics that enable it to penetrate microbial membranes and deliver drugs due to its small size, making it more effective and less harmful [34]. For example, the integrated silver and silica nanocomposite acts as a powerful antimicrobial agent by continuously releasing silver ions and disrupting and inhibiting the microbial cell walls, making it an important mechanism for effectively inhibiting microbes [35-36]. Nanoparticles of a peptide and cationic nature, possessing a charge and a helical or sheet-like shape, can penetrate the surface of bacterial cells and cause infection. Since they possess these properties, once they penetrate the cells, they neutralize their negative charges, thus forming amphipathic peptides that give them antibacterial properties. This was demonstrated against *Staphylococcus aureus* in experiments conducted on mice [37]. Alternative treatments must be found to eliminate bacteria and reduce their spread and resistance to traditional treatments. One of the modern alternatives is to mix nanoparticles with natural compounds such as honey, oils, and others, making them more active and effective [88]. Some research has mentioned the possibility of encapsulating essential oils (such as thyme oil or oregano oil) and assembling carrier systems for nanoparticles and adding them to food industries, such as natural juices, making them antibacterial without compromising the nutritional quality of the product [38-39]. Furthermore, the addition of benzoic acid at a concentration of 1100 µg/ml to polylacticoglycolic acid nanoparticles helps inhibit the growth of *Listeria monocytogenes*, *Salmonella Typhi*, and *Escherichia coli* bacteria from the raw materials [40]. It has been shown that the nanocarriers were able to deliver benzoic acid and inhibit bacterial colony numbers. In *Salmonella Typhi* and *Listeria monocytogenes* samples cultured after 9 and 14 days of storage, a decrease in the number of *Salmonella Typhi* and *Listeria monocytogenes* was observed compared to those cultured without nanoparticles. Titanium dioxide (TiO₂) and silver oxide (Ag₂O) nanoparticles exhibit high efficacy against bacteria. They may also be effective against eukaryotic pathogens [41-42]. Silver nanoparticles can also be produced using a simple and environmentally friendly method called green synthesis. Their antibacterial efficacy against *Escherichia coli* and *Penicillium* species has been proven. Comparisons with other pathogens were evaluated using the disk diffusion method [43-44]. The mechanism by which nanoparticles affect bacteria begins with a series of processes. For example, silver particles stimulate oxygen production in bacteria via silver ions. Electron transport may be impaired due to damage to cell membranes, enzymatic dysfunction, DNA fragmentation, or interaction with electron transport proteins or enzymes. Through the reaction of ions with oxygen, superoxide molecules are formed. This mechanism leads to oxygen accumulation in the cytoplasm, disrupting bacterial systems by affecting enzymes and causing oxidative stress due to oxygen buildup within bacterial cells. Furthermore, oxygen damages DNA and cell membranes, oxidizes enzymes and lipids, and ultimately leads to bacterial cell death and destruction [45]. Nanoparticles possess antimicrobial properties, including inhibition of biofilms, oxidative stress, and ion release. This mechanism is achieved through steps such as the interaction of nanoparticles with oxides present in microbial cell walls, causing damage and deterioration, or their ability to cause damage and disturbances in proteins, DNA, and enzymes as a result of the penetration of metal ions, causing cell death. They also cause oxidative stress due to the generation of reactive oxygen, which causes the death of the cell and its components and disrupts microbial antioxidant defenses. In addition, nanoparticles have the ability to prevent the formation of biofilms, thus preventing

bacteria from adhering to surfaces and reducing the development of bacterial resistance. Furthermore, nanoparticles have the ability to work synergistically by increasing the absorption of antibiotics and overcoming antibiotic resistance by disrupting the outflow pumps or reducing effective doses [89-90-91-92].

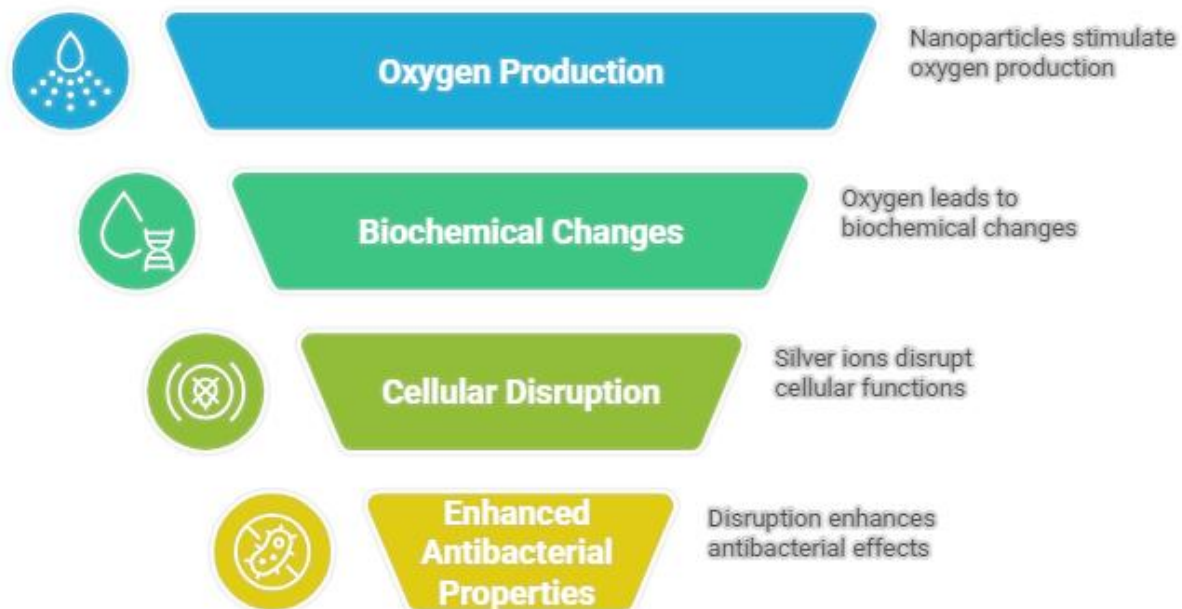


Figure 3: The stages of microbial elimination using silver nanoparticles.

5. Modern Applications of Nanomaterials as Antibacterials

Nanomaterials are increasingly being used as antibacterial agents in various fields due to their ability to effectively kill bacteria and inhibit their growth. Below are some current applications of these materials, each with supporting resources indicated:

5.1 Antibacterial Nanoparticle Coatings (Zinc Oxide/Titanium Dioxide Coatings):

Antibacterial nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO₂) are increasingly being used to coat frequently touched surfaces in clinical settings. Their antimicrobial activity is essentially based on a photocatalytic mechanism: When activated by UV light, these semiconductor materials produce reactive oxygen species (ROS) such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide anions (O_2^-). These compounds are characterized by their ability to oxidize and stimulate the release of ions. When they penetrate the surface of bacterial cells, they break down lipids and damage DNA, thus limiting bacterial growth [46]. Studies have indicated that some nanomaterials, such as zinc oxide (ZnO) and titanium dioxide (TiO₂), exhibit activity against *Staphylococcus aureus*, *Escherichia coli*, and other types of bacteria. To enhance their effectiveness, they must be stabilized by mounting them on zeolite 4A substrates or titanium nanotubes. Some studies have also shown that TiO₂/ZnO compounds are effective against microbes, with zinc oxide nanoparticles exhibiting more potent antibacterial effects than titanium dioxide. Table 1 shows some comparisons between nanomaterials [73-74]. As for potential concerns and their impact on the environment, these remain, especially since studies have shown that their activity increases with the presence of ultraviolet radiation and decreases in areas lacking such radiation.

Table 1: Comparison of Nanomaterials in terms of mechanism of action, size, and effectiveness[80-81].

Nanomaterial	Type	Mechanism of Action	Size	Effectiveness	Application
nano-SiO ₂	Pozzolanic	Develop compressive strength	Smaller particles	More effective	Cement-based materials
nano-TiO ₂	Non-pozzolanic	Reduces harmful pores	N/A	Increase impermeability	Cement-based materials
Selenium nanoparticles	Metal	Antibacterial activity with ATP depletion and ROS induction	About 81 nm	Preferable	Biomedical applications
Metal nanoclusters	Metal	Antibacterial effects dependent on size and surface charge	vary	impact bacterial interactions	Biomedical applications
Selenium nanomaterials	Non-metal	Cytotoxicity and cellular uptake are affected by shape and aspect ratio	Spherical nanorods	Higher toxicity	Biomedical applications
Organic and inorganic nanomaterials	Organic/Inorganic	Enhances targeting and immune modulation	N/A	N/A	Drug delivery and tumor immunotherapy

5.2 Antibacterial Nanocomposite Plastics:

Nanomaterials are characterized by their ability to resist bacteria and are generally antibacterial, hence the modern trend of combining them with plastics and using them in multiple fields, such as medicine, agriculture, industry, and others. As a double-edged sword, concerns about environmental pollution are possible as a result of recycling plastics, as well as the impact on humans [47], as shown in Figure 4.

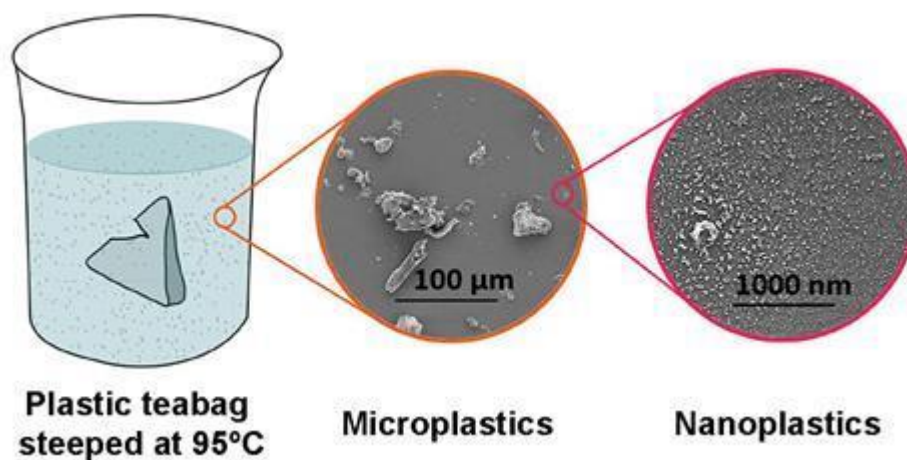


Figure 4: Thermal decomposition of plastic in tea bags and release of microplastic and Nanoplastic [48].

Studies have shown that combining polylactic acid (PLA) with graphene oxide and silver nanoparticles (GO-AgNPs) results in a mixture with exceptional strength, high thermal stability, and antibacterial activity against pathogenic bacteria such as *Escherichia coli* and *Staphylococcus aureus*, making it an ideal choice for medical applications. Polyvinyl alcohol (PVA) combined with GO-AgNPs also exhibits excellent thermal and mechanical properties, along with antibacterial activity, making it a superior choice for wound dressings. Furthermore, polypropylene (PP) combined with polyaniline/graphene or chitosan and

silver nanoparticles demonstrates effective antibacterial activity while maintaining or enhancing its mechanical strength [75-76-77].

5.3 Antibacterial Nanofibers:

Given that nanoparticles are antibacterial and antimicrobial, nanofibers can be incorporated into fabrics and textiles, and thus can be used in public health facilities due to their ability to fight microbes, as illustrated in Table 2. However, the possibility of these nanomaterials leaking out remains due to daily consumption and the use of washing materials [49], as shown in Figure 5.



Figure 5: Parts of the Nanofiber [50]

Table 2: Classification of antimicrobial agents and their applications in Nanofibers and protective textiles

Material Type	Antimicrobial Agents	Application	Mechanisms	Key Properties
Nanofibers	Silver, Zinc Oxide, Copper, Curcumin, Plant Extracts	Wound bandages	Ion release, Physical disarray, Generation of reactive species	Rise surface area, Improved mechanical properties, Biocompatibility[78].
Textiles	Compact electrospun nanofibers	Preservative textiles	Ion release, Physical disarray	Strong antibacterial activity after washing[79].

5.4 Use of Nanomaterials in Water Treatment:

Studies have indicated good results regarding the use of nanomaterials in supporting water health and purity by adding them to filtration filters to eliminate bacteria, but risks are still possible from water contamination by nanomaterial particles and their leakage into nature or their entry into the human body and their interaction with its cells [51], as shown in Figure 6.

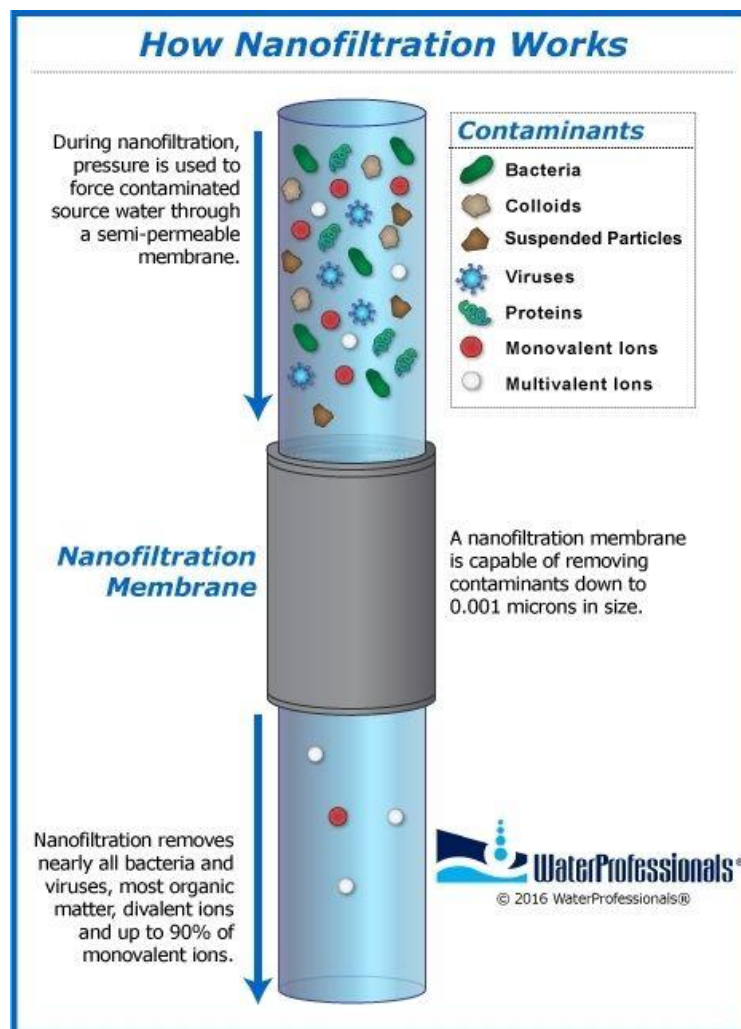


Figure 6: The role of Nanofiltration membranes in removing microbial and ionic pollutants from water [52]

5.5 Nanoparticle-Based Drug Delivery Systems:

One of the advantages of nanoparticles is their ability to deliver antibiotics to the site of infection, thus increasing the possibility of treatment and reducing side effects. They can also reduce systemic exposure and increase the concentration of the local drug [53]. These systems are used in cancer treatment and have shown promising results by increasing the drug's half-life, reducing systemic toxicity, and precisely targeting tumor sites. However, challenges exist, such as the limited drug delivery capacity and stability of the nanoparticles [93].

5.6 Nanocoating for Medical Equipment:

As a solution to the adhesion of microbes to medical instruments and hospital surfaces, nanoparticles were used to form a strong, insulating layer to reduce the spread of infection [54]. The challenge: Coating surfaces and medical equipment, repeated use, and sterilization using various methods and types, leads to the peeling and removal of these particles, thus repeating the contamination of instruments and the body after surgical procedures or patient examinations.

5.7 Development of Biogenic Nanomaterials:

Nanoparticles can be synthesized using green methods, such as plant, fungal, or bacterial extracts. As a result of previous studies and experiments, it has been proven that nanoparticles have the ability to inhibit bacterial growth, and some types possess antibacterial properties [55]. The challenge: All findings are laboratory-based and may be affected by various factors such as the dosage and virulence of the microbes, and even the efficiency of the nanomaterial.

6. Toxicological Effects of Nanoparticles

Despite the advantages of nanomaterials and their precision in working as an antibacterial agent, concerns persist about their production of toxic substances, even though they are a double-edged sword, given their external structure, size dimensions, ability to penetrate the membranes of living organisms, and their ability to deliver drugs and target organisms [56]. The small nanoscale size can lead to varying toxicity among microbes, with sizes ranging from 30 nanometers to 3 nanometers. Therefore, the size increases the binding rate to the surface of biological cells. In addition to the size of nanoparticles, their toxicity and degree of interaction in cell biology may be affected [57]. The dimensions of the particles vary; some may have low dimensions, while others have high dimensions and different properties such as crystalline structure, surface coating, and others. These are an important factor in the renewal of toxicity and include tubes and fibers that are about 150 nanometers in size and exceed 5 micrometers in length, and they are associated with pulmonary fibrosis resulting from bacteremia and lung cancer [58].

Other factors affecting nanoparticle toxicity include solubility, particle stability, and absorption, and their mechanism of action in biological systems [59]. Liquid media can cause aggregation and clumping of materials, potentially altering their activity and effectiveness, and consequently their toxicity [60]. Thus, the toxicity of materials is determined by several factors: size, shape, aggregation, and solubility, as summarized in Figure 7.

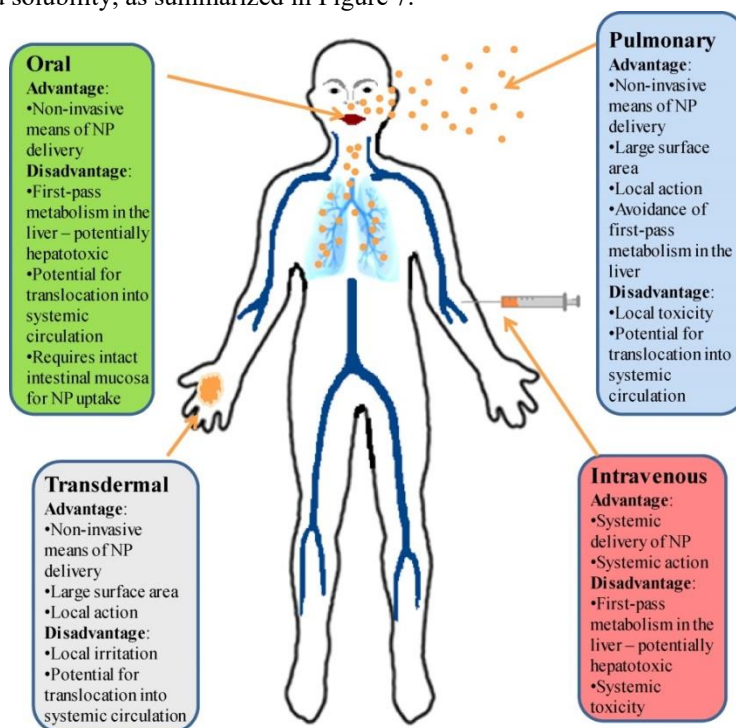


Figure 7: Administration routes to nanoparticles and their positive and negative effects [61].

7. Future challenges and research directions

Nanoengineering contributes to the development of nanoparticles and their application in various fields and multiple uses because it allows for the control of their properties and structure [62]. These materials possess unique properties in the medical field due to their ability to combat bacteria and act as antibiotics [63]. Recent studies have indicated that combining natural compounds with nanoparticles increases the activity, effectiveness, and efficiency of treatment delivery through the ability of nanobodies to deliver antibiotics or natural compounds to infected macrophages, and its effectiveness against methicillin-resistant *Staphylococcus aureus* (MRSA) has been proven [64]. Many nanomaterials, such as silver and zinc oxide, are effective, especially when combined with certain plant oils, as in the case of *Pseudomonas aeruginosa*, which may be a promising solution for overcoming bacterial resistance [65], as shown in Figure 8. Recent studies have shown the following:

- **Membrane disruption:** This helps to expel cell contents. Studies have shown that solid lipid nanoparticles can carry eugenol [66].
- **Oxidative stress:** These nanoparticles can produce oxygen, thus affecting the protein and DNA of pathogenic cells.
- **Biofilm inhibition:** They disrupt biofilms, preventing adhesion and thus weakening their ability to cause infection [67].

The active and effective properties of nanoparticles can be sufficient to limit the growth and spread of pathogens. However, their size, shape, surface charges, and combination with other compounds should be carefully considered to enhance their effectiveness.



Figure 8: Future challenges and Environmental and Health concerns of Nanotechnology

8. Discussion

The aim of using nanotechnology is to combat and overcome bacterial infections, as well as to pave the way for the development of alternative, rapid, and targeted treatments in multiple ways to fight bacteria, such as destroying cell membranes and walls, among others [68]. Many nanomaterials have proven effective in combating infections, but silver, gold, and zinc oxide nanoparticles are among the best [69]. The use of nanomaterials in the production of nano- or biosynthetic therapies is somewhat costly due to the need for comprehensive studies to ensure their safety in clinical use or because of somewhat complex and time-consuming manufacturing processes, which means that incorporating them into therapies as an antibacterial agent will be a burden on individuals or institutions [94]. On the other hand, the risks of nanomaterial toxicity are still present. Therefore, we need more studies to know the effect after consuming these particles, despite proving their effectiveness with natural alternative treatments, and increasing the speed of their effectiveness and reaching the goal [70-71]. Nanoparticles have contributed to the development of technologies used in medicine, biotechnology, and laboratories due to their use in highly accurate and efficient diagnosis, early detection of diseases and tumors, treatment delivery, and even imaging, thanks to their small size, properties, and structure. Furthermore, nanoparticles, such as silver nanoparticles, can be linked to specific proteins, peptides, or carrier proteins, enabling them to target bacterial cells or infected tissues like tumors. Some nanoparticles used as nanocarriers have been developed, such as liposomes, dendrimers, and polymeric nanoparticles, in addition to smart nanoparticles designed based on responding to biological stimuli, which work based on target delivery and therapeutic efficacy with the possibility of reducing damage to healthy tissues [82]. There are other types of treatments called nanodynamic therapies (NDTs), photodynamic therapies, acoustic therapies, radiodynamic therapies, and chemodynamic therapies. These work with the presence of sensitizing materials that are activated by external or internal stimuli to generate reactive oxygen species in order to eliminate cancer cells while reducing the side effects of chemotherapy and the toxicity of cancer cells [83]. Recent studies have shown that the synergy of these nanoparticles with antibiotics increases their effectiveness by 86%. All studies have demonstrated the efficacy of nanomaterials in delivering antimicrobial therapies by improving drug aggregation at the site of infection, delivering antibiotics to phagocytic cells, and reducing infection and its spread. Some nanoparticles coated with biopolymers exhibit potent antimicrobial activity by disrupting metabolism, inhibiting reactive oxygen species, and suppressing biofilms. Furthermore, nanoparticles can carry natural compounds such as berberine and chlorogenic acid and have demonstrated strong inhibition of multidrug-resistant MRSA bacteria compared to conventional antibiotics. They also aid in wound healing. The synergistic effect of nanoparticles with antimicrobial therapies holds great promise for therapeutic delivery, targeted therapy, and overcoming acquired microbial resistance to antibiotics [95-96-97-98-20]. The industrial sector has witnessed tremendous progress and an increase in the application of nanomaterials in the field of industry, such as synthetic dyes, construction, textiles, aviation, oil

and gas, computers, dyes, energy-saving devices, and smart sensing systems. For example, an initiative was launched in Canada called the "Nano House" with the aim of building an environmentally friendly house that reduces maintenance costs for the coming years. The proposals were to use basic materials containing nanomaterials, such as fibers and polymers in concrete and cement and mix them in a way that uses sound energy to ensure distribution and integration with cement to increase the strength and durability of the house, as well as the use of titanium dioxide and carbon nanotubes, Nanotechnology has contributed to the development of textiles and the creation of new, high-specification fabrics. For example, the Swiss company Schuler has produced "Soft Shells" branded fabrics, distinguished by their elasticity and multi-layered construction. Nanomaterials can also be added to fabric coatings, resulting in smart textiles with multiple functions, such as filtration fabrics, chemical protective suits, civil defense uniforms, and wound dressings. These wearable fabrics are equipped with solar-powered batteries, and graphene is used in battery manufacturing, leading to fabrics enhanced with sensors. Furthermore, titanium dioxide and zinc oxide nanoparticles are used to absorb, dissipate, and block ultraviolet radiation from textiles, making them more efficient [99]. In agriculture, nanotechnology has contributed to protecting crops, detecting and monitoring plant pathogens, toxins, and pesticides, improving soil quality to increase production, and extending shelf life in food packaging. This is achieved by incorporating silver nanoparticles into packaging materials, making them antibacterial and antifungal against food spoilage microorganisms. Additionally, clay and silica nanoparticles are used as materials that enhance oxygen and moisture barrier properties, preventing microbial growth and food spoilage, thus ensuring crop protection. However, this technology still faces concerns and challenges regarding its environmental impact, potential toxicity, regulatory issues, and its feasibility and production capacity. [100]. Despite this tremendous development and its benefits across numerous fields, further research is needed regarding nanomaterials, their toxicity, their environmental impact, and the need for skilled personnel to handle these particles [72].

9. Conclusion

This work provides a valuable overview of the role of nanotechnology in antimicrobial therapies and highlights its potential applications across multiple scientific fields. It explores various types of nanomaterials and their applications, including their effectiveness as antibiotics and the concept of combining them with other active ingredients, whether natural or other nanomaterials, to enhance antimicrobial efficacy. The work also examines their use in diverse sectors such as textiles, plastics, agriculture, carbon nanotubes for irrigation, and medicine for specific purposes like cancer treatment. However, concerns remain regarding their toxicity, size, and minuscule nature. These particles are a double-edged sword due to their properties. They can penetrate any surface and may damage the components of living cells, both human and microscopic. Therefore, further research and future applications are needed to mitigate these potential risks.

10. Declarations

10.1 Ethics approval and consent to participate

Not application

10.2 Consent for publication

Not application

10.3 Availability of Data and Materials

Data will be provided upon receiving a valid request.

10.4 Conflicts of interest

The authors declare that there is no conflict of interest

10.5 Funding

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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دور تقنية النانو في علم الأحياء الدقيقة: ثورة علمية في العلاجات المضادة للميكروبات

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المستخلص

يتناول هذا العمل البحثي العلاقة بين علم الأحياء الدقيقة وتقنية النانو، مستكشفة تطبيقاتهما وتأثيرهما في مختلف المجالات، بما في ذلك الطب والزراعة والصناعة. وتدرس خصائص وبنية الجسيمات النانوية، وتأثيراتها، وأكثر المواد المضادة للبكتيريا فعالية. كما تناقش المقالة الآليات العامة لعمل هذه الجسيمات، بما في ذلك دورها في تحفيز إطلاق الأيونات، والعمليات المؤكسدة وغير المؤكسدة، ووظيفتها داخل الخلايا، وتحديد قدرتها على تثبيط نمو البكتيريا أو قتلها أو الحد منه. علاوة على ذلك، تتناول المقالة مزايا وعيوب الجسيمات النانوية، على الرغم من النتائج الواعدة التي أظهرتها العديد من الدراسات الحديثة، والمخاوف المحتملة الناجمة عن استخدامها في مجالات متنوعة وتأثيرها البيئي. وعلى الرغم من التكاليف الباهظة، فإن تطور تقنية النانو وهندسة النانو يبشر بمستقبل واعد. كما تتناول المقالة فعالية العلاجات البديلة والطبيعية، مثل العسل والزيوت العطرية، ودمج الجسيمات النانوية معها لزيادة فعاليتها ونشاطها البيولوجي في القضاء على البكتيريا المسببة للأمراض.