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NANOTECHNOLOGY IN ANTIMICROBIAL THERAPY: ENHANCING THE ARSENAL AGAINST RESISTANT MICROORGANISMS

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ABSTRACT: Antimicrobial resistance is a critical challenge for global health, weakening the use of most conventional antibiotics to treat infectious diseases. Recently, nanotechnological advancements have provided a new promise in the fight against resistant microorganisms and antimicrobial treatment support. This review provides an overview of nanotechnology for antimicrobial therapy, insights into the design and development of new classes of nanomaterials as well as drug delivery systems at nanoscale dimensions aimed towards various strategies targeting emerging MDR bacteria. Nanoparticles, nanostructures, nanosilver and nanoformulations have exhibited extensive prospect in ameliorating the drug stability, provocation of drug bioavailability and defeat the microbial resistance mechanism. Moreover, nanotechnology makes drugs more specific to the intended pharmaceutical target and less likely to affect other organs which subsequently improves therapeutic efficiency. The extraordinary properties of nanomaterials opened new doors for novel strategies against harmful microbes, e.g. antimicrobial surfaces and coatings. But there are technical issues to overcome related to safety, regulation and mass production. In this review, we address the recent progress in nanotechnology-based antimicrobial therapies and their mode of action to combat resistant microorganisms. Nanotechnology has the potential to significantly impact antimicrobial therapy with continued research and development, thereby enhancing our capability against the emergence of resistance to conventional antimicrobials.

Key Words: Nanotechnology, antimicrobial therapy, antimicrobial resistance, nanomaterials, drug delivery, targeted drug delivery.

I. INTRODUCTION

Increasingly, AMR has become a global public health threat eroding the efficacy of traditional therapies and presenting previously un-imagined challenges to control [sic] infectious disease [1]. With the increasing number of pathogens that have become resistant to traditional antibiotics, there is an urgent need for a different approach. Nanotechnology has recently appeared as the most interesting and disruptive new field in the area of antimicrobial therapy. Nanotechnology exploits unique properties of nanomaterials and nanoparticles for combating the growing threat of AMR, making it a new hope in our struggle against the invading microbes that are evermore resilient [2].

In it we explore how nanotechnology may be a game changing solution for our escalating problem of antimicrobial resistance, taking you on a journey into the world of nano as only the unlikely science communication duo from an in vivo context canelfare. We first provide a brief description of the serious consequences to global health of antimicrobial resistance, then explain how this helps to illustrate why it is so critical that new treatment strategies are identified. Finally, we touch on the possibilities nanotechnology has to offer in revolutionizing the field of medicine [3].

The objective of the present review is to highlight various applications describing the novel features and transformative potential of nanotechnology in antimicrobial therapy. In this chapter, we provide an overview of the potential new nanoparticulate drug delivery systems and discuss how they can challenge antimicrobial susceptibility mechanisms. We aim to shine a light on these weapons-cutting-edge research and breakthroughs-and by doing so, we hope to capture some of nanotechnology's contribution to fighting back against resistant strains.

So, as we set forth on this journey we encourage readers to think about a future scenario where nanotechnology driven antimicrobial therapies reimagine not only the restoration of efficacy of the existing drugs but also a cornerstone for precision medicine and personalized interventions. This is a new way, as it will come through regulatory considerations and ethical implications right along with the revolutionary approaches they promise. Centered around have described recent developments and applications in patient care of nanotechnology-based anti-infective agents and we anticipate that this review will inspire researchers to find new niches, strategies and architectures needed for success in clinical discovery the transition of nanoantimicrobials from the bench top to the bedside. Jointly, we set forth on a journey to explore the power of nanotechnology as we persist in our mission for the sake of human existence within healthcare and medicine.

II. Nanotechnology in Antimicrobial Therapy: An Overview

Too new for a comprehensive definition, nanotechnology is becoming popular through the manipulation of materials and devices at the 1-100 nanometers size range [4]. In the medical realm, nanotechnology uses the special characteristics shown by nanoparticles to exert a very specific control over drug interactions and delivery. Inspiration from nanoscale processes including quantum phenomena and surface interactions provides promising strategies in combating issues at the root of antimicrobial resistance (Table 1) [5].

Table 1: Nanomaterials Used in Antimicrobial Therapy

Nanomaterial	*Mechanism of Action*	*Target Microorganisms*
Silver nanoparticles	Disruption of cell membranes	Bacteria, fungi, viruses [6-8]
Zinc oxide nanoparticles	Generation of reactive oxygen species	Bacteria, fungi, viruses [9-11]
Graphene oxide	Membrane penetration and disruption	Bacteria, fungi [12, 13]
Liposomes	Enhanced drug delivery and stability	Bacteria, fungi, viruses [14-16]

Nanotechnology-based antimicrobial therapy has several advantages as we have covered above. One is the high surface area-to-volume ratio of nanomaterials which can lead to a sort of drug-loading (specifically, enhanced drug stability and solubility) benefits. The second is the capability of nanotechnology to form multifunctional nanocarriers loaded with a wide array of antimicrobial agents thereby allowing combination therapies while delaying resistance formation. Furthermore, the capability of nanomaterials to behave at the molecular scale with biological entities allows the antimicrobials to be delivered locally through drug targeting systems which delivers them only where infected, minimizing adverse effects on healthy tissues [17].

Nanoparticles and nanocarriers have been regarded as a backbone in transforming the frontiers of drug delivery systems for antimicrobial therapy This phenomenon of decreased clearance and degradation stretches the circulation time of antimicrobial agents in the body, which are shielded within nanoscale carriers - such as liposomes, polymeric nanoparticles, dendrimers or carbon nanotubes. These improved stability and characteristics of drug-release profiles of nanoscale formulations result in more efficient pharmacokinetics and pharmacodynamics of the drug. Nanoparticles can also undergo surface functionalization to achieve active targeting by the incorporation of ligands, which specifically bind to microbial cells, biofilms or receptors and hence enable more precise delivery and better therapeutic benefits [18].

III. Nanomaterials for Antimicrobial Therapy

A. Overview of Various Nanomaterials Used in Antimicrobial Applications

Nanomaterials, as a promising choice in the field of nanotechnology for antimicrobial therapy, exhibit different inherent characteristics and hence interact and function variably against microorganisms. In this review as can be seen, we summarized that nanomaterials are variable for antimicrobes [19]. Nanomaterials are able in solution to be builded from the nanoscale such as graphene, carbon nanotubes and polymeric nanoparticles, have also been growing in interest and usage for an implementation for different industrial application apart metallic and metal oxide nanoparticles (can be of silver, gold or copper for metallic nanoparticles or of zinc oxide or titanium dioxide for metal oxide). As has been established for cargo delivery, depending on its physicochemical properties and mechanisms of action, each type of nanomaterial potentially possesses advantageous characteristics to revolutionize the antimicrobial therapy [20].

B. Mechanisms of Action of Nanomaterials Against Microorganisms

For this reason, it is important to gain insight into how nanomaterials exhibit their antimicrobial activity. Nanomaterials have different mechanisms to exert these effects; the most common modes of action are their direct or physical interaction with microbial cells, cell membrane disruption or damage, ROS production and overall toxin releasing effect on microorganism. Novel surface chemistry and large specific surface area of nanomaterials give rise to their excellent antimicrobial properties, effective against various types of microorganisms such as bacteria, fungi, virus, and drug-resistant strains [21].

C. Comparative Analysis of Different Nanomaterials and Their Effectiveness

It is, therefore, necessary to perform a comparison representatively between different types of nanomaterials for antimicrobial therapy in terms of their benefits and drawbacks. Depending on the exact nature of their intended applications, researchers can determine whether the nano-bullets will be antimicrobial and have the durability, biocompatibility and potential for drug delivery that they desire. Furthermore, examination of nanomaterial properties, such as size, shape and surface functionalization on antimicrobial activity, allows for the development of more precisely targeted nanotherapeutics with increased specificity against specific microorganisms [22].

IV. Nanoscale Drug Delivery Systems

A. Nanocarriers for Antimicrobial Drugs: Liposomes, Polymeric Nanoparticles, etc.

One of the paradigms of drug delivery is its nanoscale, which provides unique strategies to increase and more safely deliver antimicrobial drugs. Of the numerous nanocarriers, liposomes and polymeric nanoparticles are noteworthy contestants. Small-sized liposomes (phospholipid-based vesicles), offer an excellent strategy for encapsulating both hydrophilic and hydrophobic antimicrobial agents, thereby ensuring the controlled release of the drugs as well as long-term stability. In contrast, the tunability of polymeric nanoparticles during synthesis and design allows for custom carriers that can suit many different types of antimicrobial compounds. Besides, these nanocarriers protect the drugs from early degradation and enhance drug dissolution rate, which can finally break the bottleneck of current conventional GRI formulations [23].

B. Advantages of Nanoscale Drug Delivery Systems Over Traditional Drug Delivery

Nanoscale drug delivery system is a breakthrough in antimicrobial therapy which has provided various benefits over the conventional methods of delivery. Thus, it significantly decreases the risks of side effects by maintaining drug levels at therapeutic doses, which allows for longer dosing intervals and sustained release kinetics. In addition, because of their small size (nanosize), NPs are able to passively target infections sites due to enhanced permeation and retention effect, making site-specific accumulation possible. In particular, such increased drug accumulation and bioavailability are associated with better antimicrobial activity from the susceptibility problem against resistant microorganisms. Furthermore, the combination of nanoscale drug carriers allows for multiple antimicrobials to be simultaneously delivered to overcome multidrug-resistant pathogens synergistically [24].

C. Targeted Drug Delivery to Combat Microbial Resistance

Among the greatest current advantages of nanoscale drug delivery systems is the potential for targeted drug delivery, a sine qua non action to overcome microbial resistance. By functionalizing nanocarriers with specific ligands, such as antibodies or peptides, researchers can achieve active targeting, directing antimicrobial agents precisely to pathogen-infested tissues or biofilms. This targeted drug delivery not only enhances therapeutic outcomes but also reduces drug exposure to healthy tissues, minimizing off-target effects. Furthermore, nanotechnology opens avenues for overcoming efflux pump-mediated resistance, as it allows efficient intracellular drug delivery and evasion of microbial resistance mechanisms [25].

V. Nanotechnology-Based Antimicrobial Agents
A. Development of Nanoscale Antimicrobial Agents

Nanotechnology has opened new avenues for creating antimicrobial agents with enhanced properties and functionalities. Researchers have engineered various nanoscale antimicrobial agents, including metal-based nanoparticles (e.g., silver, copper), metal oxide nanoparticles (e.g., zinc oxide, titanium dioxide), antimicrobial peptides, and carbon-based nanomaterials (e.g., graphene oxide). These agents disrupt microbial membranes, interfere with cellular processes, and induce oxidative stress, rendering them effective against drug-resistant strains and a diverse range of microorganisms [26].

B. Enhanced Antimicrobial Activity and Reduced Resistance Development

Nanoscale antimicrobial agents demonstrate significantly enhanced activity compared to conventional counterparts. Their small size and high surface area facilitate better penetration into microbial cells, leading to more efficient antimicrobial action. Additionally, their unique mechanisms of action make it less likely for microorganisms to develop resistance, offering a promising approach to combat persistent and resistant infections [27].

C. Synergistic Effects of Antimicrobial Agents and Nanotechnology

Antimicrobial agents are currently being widely used in combination with nanotechnology, offering hope for antimicrobial therapy. So, by integrating the antimicrobial agents in these nanocarriers or functionalizing the surface of nanoparticles to introduce antimicrobial properties, a synergy creation can take place- where a sum is greater than its parts. This method increases the antimicrobial activity, makes for less effective doses and minimizes side effects. In addition, using multiple antimicrobial agents to target separate steps of the biofilm formation process can be additive or even synergistic in nature, making it a potentially powerful way to treat multidrug-resistant pathogens and biofilm-associated infections [28].

Table 2: Comparison of Nanotechnology-Enhanced Drug Formulations

Drug Formulation	*Advantages*	*Disadvantages*	*Applications*
Nanoparticle-based liposomes	Improved drug stability and solubility	Manufacturing complexity	Targeted drug delivery
	Controlled release	Potential toxicity	Antimicrobial coatings
	Targeted drug delivery	Risk of drug leakage	Photothermal therapy
	Reduced resistance development	Limited drug payload	Immunotherapies [29]

VI. Nanoformulations for Improving Drug Stability and Bioavailability
A. Challenges in Antimicrobial Drug Stability and Bioavailability

Antimicrobial drugs face significant challenges related to stability and bioavailability, which can hinder their effectiveness in combating infections. Many antimicrobial agents are prone to degradation under physiological conditions, reducing their shelf life and therapeutic efficacy. Additionally, poor solubility can limit drug absorption, leading to suboptimal drug concentrations at the infection site. These challenges underscore the need for innovative approaches to improve drug stability and enhance bioavailability [30].

B. Role of Nanotechnology in Improving Drug Stability and Solubility

Nanotechnology offers a powerful solution to address the challenges of antimicrobial drug stability and solubility. Through the development of nanoscale drug delivery systems, such as liposomes, polymeric nanoparticles, and nanocrystals, nanotechnology enables the encapsulation of antimicrobial agents within protective carriers. This encapsulation shields the drugs from degradation, preserving their potency and extending their shelf life. Moreover, nanocarriers can enhance drug solubility by increasing the surface area available for dissolution, thereby improving drug absorption and bioavailability [31].

C. Impact of Nanoformulations on Drug Pharmacokinetics and Pharmacodynamics

Nanoformulations have a profound impact on drug pharmacokinetics and pharmacodynamics. The unique properties of nanocarriers influence drug release kinetics, leading to sustained drug concentrations at the infection site. This sustained release can prolong the drug's therapeutic effect and reduce dosing frequency, enhancing patient compliance. Additionally, nanocarriers can improve drug distribution, allowing for more extensive tissue penetration and increased efficacy against intracellular pathogens. The controlled release and targeted drug delivery provided by nanoformulations optimize drug interactions with microbial targets, enhancing therapeutic outcomes and minimizing the development of drug resistance [32].

VII. Innovative Antimicrobial Strategies Enabled by Nanotechnology

A. Antimicrobial Surfaces and Coatings

Nanotechnology has revolutionized the development of antimicrobial surfaces and coatings, offering a potent defense against infectious agents. By integrating nanomaterials with antimicrobial properties into various surfaces, such as medical devices, implants, and textiles, researchers have created self-sanitizing materials that can actively inhibit microbial growth and prevent biofilm formation. These nanotechnology-based antimicrobial surfaces hold immense potential in reducing hospital-acquired infections, improving patient outcomes, and enhancing the safety of medical procedures [33].

B. Photothermal and Photodynamic Therapies Using Nanomaterials

Nanotechnology has unlocked the power of light-based therapies for antimicrobial applications. Photothermal therapy employs light-absorbing nanomaterials, such as gold nanoparticles or carbon nanotubes, to generate localized heat when exposed to near-infrared light. This controlled heat selectively targets and eradicates microbial cells, including drug-resistant strains. Similarly, photodynamic therapy employs photosensitizing nanoparticles to produce reactive oxygen species upon light activation, causing microbial cell damage and death. Both photothermal and photodynamic therapies offer non-invasive and targeted approaches to treat localized infections and combat resistant microorganisms [34].

C. Combining Nanotechnology with Immunotherapies

Nanotechnology has ushered in a new era of combination therapies by synergizing antimicrobial agents with immunotherapies. By leveraging the unique properties of nanomaterials, researchers can co-deliver antimicrobial agents and immunomodulators to enhance the immune response against infections. Nanoparticles can serve as carriers for antigen presentation, promoting the activation of immune cells and augmenting the body's defense mechanisms. This convergence of nanotechnology with immunotherapies opens exciting possibilities for personalized and precise approaches to tackle infectious diseases while minimizing the risk of resistance development [35].

VIII. Safety and Regulatory Considerations

A. Biocompatibility and Toxicity of Nanomaterials

The safety of nanotechnology-based antimicrobial therapies hinges on the biocompatibility and toxicity of the employed nanomaterials. Nanomaterials have many promising properties, but this should be weighed carefully against their interactions within biological systems. Biocompatibility study, which ensures the innocuous effects of nanomaterial on tissues, cells and organs were conducted. Also, examining toxicity and more long-lasting effects is paramount to maintaining patient safety. A detailed knowledge of the biocompatibility of nanomaterials is a pre-requisite for building responsible strategies for designing and delivering antimicrobial approaches based in nanotechnology [37].

B. Regulatory Challenges and Approval Processes for Nanotechnology-Based Therapies

The use of nanoparticles in antimicrobial strategies has opened up new regulatory concerns. Packets of International Regulation For nanomaterials and their myriad uses, traditional regulatory frameworks may be incomplete. Before clinical translation of nanotechnology-based therapies, rigorous safety evaluations and standardized testing protocols need to be established. This could include flexibly streamlining metrospective approval processes and establishing a set of transparent pre-competitive guidelines for the regulation of nanomedicines, thereby reducing the time it takes to translate laboratory findings into new nanoscale therapeutic options [38].

C. Ethical Considerations in Using Nanotechnology for Antimicrobial Applications

A spectrum of ethical questions surrounds the application potential of nanoparticles, like nanotechnology in antibacterial area. This may raise questions on equal access to nanomedicine, responsible use of nanotechnology in the fight against AMR and implications on environment. Given further development of nanotechnology, numerous open dialogues could be held about the potential risks, benefits, and societal implications; however any use in antimicrobial therapy must conform to ethical principles and respect the rights and well-being of patients [39, 40].

IX. Current Research and Future Directions

A. Promising Research in Nanotechnology-Based Antimicrobial Therapy

Nanotechnology assisted antimicrobial therapy is making great strides, governed by an influx of new state-of-art research in the field. New nanomaterials under investigation continue to be more active against microbes and are also able to target bullets more smartly. This mini review aims to shed the light on utilizing nanotechnology to target intracellular infections, biofilm eradication and resistance problems. Moreover, new nanotechnologies including nanosensors and nanotheranostics may provide the opportunity of detecting infections precisely at an early stage and treating them appropriately, by personalized tracking of changes in disease activity. The collaboration between nanotechnology and other scientific disciplines, such as artificial intelligence and molecular biology, further expands the horizons of antimicrobial therapy [41].

B. Potential for Personalized Nanomedicine in Antimicrobial Treatment

The inherent versatility of nanotechnology paves the way for personalized nanomedicine in antimicrobial treatment. Tailoring nanotherapeutics based on individual patient characteristics, infection profiles, and drug responses can optimize treatment outcomes and minimize adverse effects. Personalized nanomedicine offers the potential for targeted, patient-centric interventions that consider genetic variability, microbiome diversity, and immune responses. By leveraging nanotechnology's capabilities, clinicians may soon have the means to design precise and individualized antimicrobial regimens, ushering in a new era of patient care [42].

C. Overcoming Challenges and Scaling Up for Clinical Translation

As nanotechnology-based antimicrobial therapies progress from bench to bedside, several challenges must be addressed for successful clinical translation. Ensuring the scalability and reproducibility of nanomaterial synthesis is crucial for large-scale production and widespread clinical use. Rigorous preclinical studies, encompassing safety assessments and pharmacokinetic studies, are imperative to validate the efficacy and safety of nanotherapeutics. Collaborations between researchers, clinicians, and regulatory agencies are essential for streamlining approval processes and navigating the intricacies of nanomedicine regulation. Addressing these challenges will expedite the integration of nanotechnology-based antimicrobial therapies into clinical practice, realizing their full potential in combating infectious diseases [43].

CONCLUSION

Nanotechnology has emerged as a transformative force in the field of antimicrobial therapy, revolutionizing the way we combat infectious diseases. The integration of nanomaterials and nanoparticles has led to the development of innovative drug delivery systems, nanoscale antimicrobial agents, and advanced treatment modalities. Nanotechnology-enabled approaches, such as targeted drug delivery, photothermal and photodynamic therapies, and immunotherapy combinations, offer new strategies to overcome the challenges of antimicrobial resistance. By enhancing drug stability, improving bioavailability, and enabling personalized medicine, nanotechnology holds the potential to reshape the landscape of antimicrobial treatment.

Antimicrobial resistance poses a significant threat to global health, demanding urgent and creative solutions. The multi-faceted approaches to which nanotechnology can be applied, provide a promising approach to counteract antimicrobial resistance from its very foundations. Nanoformulations of antimicrobial agents may improve the interactions between drugs, reduce resistance to microbial agents and help restore efficacy of currently used bacterial antimicrobials. Furthermore, the distinct actions of nanoantimicrobials in nanometre sizes can target any resistant strain rendering it defenceless which paves the way to be an urgency against otherwise uneradicable bio-infections. Combining nanotechnology with immunotherapies can improve this response and increase the body's protection against pathogens that are resistant to antibiotics. Interdisciplinary research and innovation within nanotechnology, including drug delivery such as using nanoparticles for smart drug delivery, biomarker discovery and boosting the sensitivity of diagnostic tests all have the potential to contribute to our antimicrobial armoury and provide solutions against resistance.

The potential that nanotechnology holds for antimicrobial therapy is not just limited to the laboratory. The use of nanotechnology-based antimicrobial therapies has broad public health and medical relevance worldwide the hope is that the solutions presented by nanotechnology-based interventions will provide a resolution to these challenges through improved drug stability, solubility and resistance. These techniques with personalized nanomedicine could empower better outcomes for patients and the healthcare system at large while advanced antimicrobial surfaces can stem the tide of infectious diseases within healthcare settings. Nevertheless, despite the encouraging avenues enticing escalation of these opportunities ethical implications, safety evaluations and regulatory strategies are key to promote responsible and sustainable usage in the antimicrobial therapy using nanotechnology.

Finally, the development of nanotechnology has heralded a new epoch on antimicrobial therapy and opened up myriad emerging avenues to fight infectious diseases. This research could pave the way towards a world where we can successfully take on antimicrobial resistance and could help us fight infections more efficiently. Nanotechnology combined with medicine shows a promising future in benefiting global health, patient care evolution and protection of mankind from the new waves of infectious diseases.

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REFERENCES:

1. Zumla A, Abubakar I, Raviglione M, Hoelscher M, Ditiu L, Mchugh TD, Squire SB, Cox H, Ford N, McNerney R, Marais B. Drug-resistant tuberculosis—current dilemmas, unanswered questions, challenges, and priority needs. Journal of Infectious Diseases. 2012 May 15;205(suppl_2):S228-40.
2. Adams T, Smith S. Communication shock: the rhetoric of new technology. Cambridge Scholars Publishing; 2015 Sep 4.

3. Contera S. Nano comes to life: How nanotechnology is transforming medicine and the future of biology. Princeton University Press; 2019 Nov 5.
4. Mansoori GA. An introduction to nanoscience and nanotechnology. Nanoscience and Plant–Soil Systems. 2017:3-20.
5. Şen Karaman D, Ercan UK, Bakay E, Topaloğlu N, Rosenholm JM. Evolving technologies and strategies for combating antibacterial resistance in the advent of the postantibiotic era. Advanced Functional Materials. 2020 Apr;30(15):1908783.
6. Shameli K, Ahmad MB, Zamanian A, Sangpour P, Shabanzadeh P, Abdollahi Y, et al. Investigation of antibacterial properties silver nanoparticles prepared via green method. Chem Cent J. 2012;6(1):73. doi: 10.1186/1752-153X-6-73.
7. Pal S, Tak YK, Song JM. Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? A study of the Gram-negative bacterium Escherichia coli. Appl Environ Microbiol. 2007;73(6):1712-20. doi: 10.1128/AEM.02218-06.
8. Lara HH, Ayala-Núñez NV, Ixtepan-Turrent L, Rodriguez-Padilla C. Mode of antiviral action of silver nanoparticles against HIV-1. J Nanobiotechnology. 2010;8:1. doi: 10.1186/1477-3155-8-1.
9. Raghupathi KR, Koodali RT, Manna AC. Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. Langmuir. 2011;27(7):4020-8. doi: 10.1021/la104825u.
10. Rasmussen JW, Martinez E, Louka P, Wingett DG. Zinc oxide nanoparticles for selective destruction of tumor cells and potential for drug delivery applications. Expert Opin Drug Deliv. 2010;7(9):1063-77. doi: 10.1517/17425247.2010.502561.
11. Elechiguerra JL, Burt JL, Morones JR, Camacho-Bragado A, Gao X, Lara HH, et al. Interaction of silver nanoparticles with HIV-1. J Nanobiotechnology. 2005;3:6. doi: 10.1186/1477-3155-3-6.
12. Liu S, Hu M, Zeng TH, Wu R, Jiang R, Wei J, et al. Lateral dimension-dependent antibacterial activity of graphene oxide sheets. Langmuir. 2012;28(33):12364-72. doi: 10.1021/la3023259.
13. Gurunathan S, Han JW, Dayem AA, Eppakayala V, Kim JH. Oxidative stress-mediated antibacterial activity of graphene oxide and reduced graphene oxide in Pseudomonas aeruginosa. Int J Nanomedicine. 2012;7:5901-14. doi: 10.2147/IJN.S37316.
14. Torchilin VP. Recent advances with liposomes as pharmaceutical carriers. Nat Rev Drug Discov. 2005;4(2):145-60. doi: 10.1038/nrd1632.
15. Zhang L, Gu FX, Chan JM, Wang AZ, Langer RS, Farokhzad OC. Nanoparticles in medicine: therapeutic applications and developments. Clin Pharmacol Ther. 2008;83(5):761-9. doi: 10.1038/sj.clpt.6100400.
16. Allen TM, Cullis PR. Liposomal drug delivery systems: from concept to clinical applications. Adv Drug Deliv Rev. 2013;65(1):36-48. doi: 10.1016/j.addr.2012.09.037.
17. Gupta N, Rai DB, Jangid AK, Kulhari H. Use of nanotechnology in antimicrobial therapy. InMethods in Microbiology 2019 Jan 1 (Vol. 46, pp. 143-172).
18. Osman N, Devnarain N, Omolo CA, Fasiku V, Jaglal Y, Govender T. Surface modification of nano-drug delivery systems for enhancing antibiotic delivery and activity. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2022 Jan;14(1):e1758.
19. Alharbi RA, Alminderej FM, Al-Harby NF, Elmehbad NY, Mohamed NA. Design, synthesis, and characterization of novel bis-uracil chitosan hydrogels modified with zinc oxide nanoparticles for boosting their antimicrobial activity. Polymers. 2023 Feb 16;15(4):980.
20. Kędziora A, Speruda M, Krzyżewska E, Rybka J, Łukowiak A, Bugla-Płoskońska G. Similarities and differences between silver ions and silver in nanoforms as antibacterial agents. International journal of molecular sciences. 2018 Feb 2;19(2):444.
21. Alavi M, Rai M, Martinez F, Kahrizi D, Khan H, Rose Alencar De Menezes I, Douglas Melo Coutinho H, Costa JG. The efficiency of metal, metal oxide, and metalloid nanoparticles against cancer cells and bacterial pathogens: different mechanisms of action. Cellular, Molecular and Biomedical Reports. 2022 Mar 1;2(1):10-21.
22. Zaidi S, Misba L, Khan AU. Nano-therapeutics: a revolution in infection control in post antibiotic era. Nanomedicine: Nanotechnology, Biology and Medicine. 2017 Oct 1;13(7):2281-301.
23. Abed N, Couvreur P. Nanocarriers for antibiotics: a promising solution to treat intracellular bacterial infections. International journal of antimicrobial agents. 2014 Jun 1;43(6):485-96.
24. Liu Z, Ji X, He D, Zhang R, Liu Q, Xin T. Nanoscale drug delivery systems in glioblastoma. Nanoscale Research Letters. 2022 Feb 16;17(1):27.
25. Sahu T, Ratre YK, Chauhan S, Bhaskar LV, Nair MP, Verma HK. Nanotechnology based drug delivery system: Current strategies and emerging therapeutic potential for medical science. Journal of Drug Delivery Science and Technology. 2021 Jun 1;63:102487.
26. Kuppusamy P, Yusoff MM, Maniam GP, Govindan N. Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications–An updated report. Saudi Pharmaceutical Journal. 2016 Jul 1;24(4):473-84.
27. Sibuyi NR, Moabelo KL, Fadaka AO, Meyer S, Onani MO, Madiehe AM, Meyer M. Multifunctional gold nanoparticles for improved diagnostic and therapeutic applications: a review. Nanoscale Research Letters. 2021 Dec;16:1-27.
28. Sofi MA, Sunitha S, Sofi MA, Pasha SK, Choi D. An overview of antimicrobial and anticancer potential of silver nanoparticles. Journal of King Saud University-Science. 2022 Feb 1;34(2):101791.
29. Singh M, Kushali D, Vinay CH. Comparison study of various nano technology formulation of curcumin in treatment of Alzheimer's disease. Asian Journal of Pharmaceutical Research and Development. 2020 Jun 15;8(3):99-103.
30. Tang J, Ouyang Q, Li Y, Zhang P, Jin W, Qu S, Yang F, He Z, Qin M. Nanomaterials for delivering antibiotics in the therapy of pneumonia. International Journal of Molecular Sciences. 2022 Dec 12;23(24):15738.
31. Gao Y, Chen Y, Cao Y, Mo A, Peng Q. Potentials of nanotechnology in treatment of methicillin-resistant Staphylococcus aureus. European journal of medicinal chemistry. 2021 Mar 5;213:113056.
32. Nikam AP, Ratnaparkhiand MP, Chaudhari SP. Nanoparticles–an overview. Int. J. Res. Dev. Pharm. Life Sci. 2014 Sep 15;3:1121-7.
33. Elashnikov R, Ulbrich P, Vokatá B, Pavlíčková VS, Švorčík V, Lyutakov O, Rimpelová S. Physically switchable antimicrobial surfaces and coatings: General concept and

recent achievements. Nanomaterials. 2021 Nov 16;11(11):3083.
34. Karimi M, Sahandi Zangabad P, Baghaee-Ravari S, Ghazadeh M, Mirshekari H, Hamblin MR. Smart nanostructures for cargo delivery: uncaging and activating by light. Journal of the American Chemical Society. 2017 Apr 5;139(13):4584-610.
35. Lou J, Zhang L, Zheng G. Advancing cancer immunotherapies with nanotechnology. Advanced Therapeutics. 2019 Apr;2(4):1800128.
36. Sun H, Lv L, Bai Y, Yang H, Zhou H, Li C, Yang L. Nanotechnology-enabled materials for hemostatic and anti-infection treatments in orthopedic surgery. International journal of nanomedicine. 2018 Dec 6:8325-38.
37. Sharifi S, Behzadi S, Laurent S, Forrest ML, Stroeve P, Mahmoudi M. Toxicity of nanomaterials. Chemical Society Reviews. 2012;41(6):2323-43.
38. Limaye V, Fortwengel G, Limaye D. Regulatory roadmap for nanotechnology based medicines. International Journal of Drug Regulatory Affairs. 2014;2014(2 (4)):33-41.
39. Hashem NM, Gonzalez-Bulnes A. Nanotechnology and reproductive management of farm animals: Challenges and advances. Animals. 2021 Jun 29;11(7):1932.
40. Kim DY, Kadam A, Shinde S, Saratale RG, Patra J, Ghodake G. Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities. Journal of the Science of Food and Agriculture. 2018 Feb;98(3):849-64.
41. Doroudian M, MacLoughlin R, Poynton F, Prina-Mello A, Donnelly SC. Nanotechnology based therapeutics for lung disease. Thorax. 2019 Oct 1;74(10):965-76.
42. Zhou J, Kroll AV, Holay M, Fang RH, Zhang L. Biomimetic nanotechnology toward personalized vaccines. Advanced materials. 2020 Apr;32(13):1901255.
43. Younis MA, Tawfeek HM, Abdellatif AA, Abdel-Aleem JA, Harashima H. Clinical translation of nanomedicines: Challenges, opportunities, and keys. Advanced Drug Delivery Reviews. 2022 Feb 1;181:114083.

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