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Nanoparticles-based Therapeutics for Zoonotic Diseases

AUTHORS DETAIL

Tushar Kumar Jain[1*]

[1]University of Veterinary Medicine Budapest, Hungary

*Corresponding author: tushar.vetmed@gmail.com

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Abstract

Nanoparticles have emerged as an effective tool in the treatment and mitigation of zoonotic illnesses because of their special physical, chemical, and biological characteristics. These nanoscale materials, measuring between 1 and 100 nm, provide benefits in medication delivery, targeted therapy, and improved bioavailability. Several of these methods have demonstrated promise in overcoming issues such as drug resistance, poor solubility of therapeutic agents, and the necessity for regulated release in the treatment of zoonotic illnesses caused by viruses, bacteria, and parasites. Given the escalating worldwide threat of zoonotic diseases, particularly recent pandemics like COVID-19, there is an imperative demand for novel therapeutic approaches. Nanoparticles provide a flexible framework for enhancing the effectiveness of current therapies while reducing side effects. However, the incorporation of nanoparticles in the management of zoonotic diseases still finds obstacles pertaining to safety, long-term impacts, and ethical considerations. This chapter evaluates the present status of nanoparticle-based therapeutics for zoonotic diseases, examines their benefits and drawbacks, and underscores ongoing research focused on enhancing their clinical use. Despite encouraging outcomes, deeper research is crucial to mitigate potential dangers and guarantee the safe application of nanoparticles in our global fight with diseases.

Keywords: Nanoparticles, Zoonotic diseases, Targeted therapy, Drug resistance, Nanomedicine

1. Introduction

1.1. Overview of Nanoparticles and Zoonotic Diseases

Nanotechnology has recently emerged as a rapidly evolving area of scientific significance worldwide (Shiza Malik et al., 2023). Nanoparticles are nanoscale particles with sizes varying from 1 to 100 nm. Their small size enables the scientific community to innovate more in this field and withdraw the significant concern of society (Allhoff & Lin, 2008). They provide adequate precautionary, preventative (antiviral, antibacterial, and antiparasitic), and therapeutic outcomes to address chronic and acute illnesses (Allhoff & Lin, 2008; Huang et al., 2024). The increased surface area of nano-sized materials enhances their chemical reactivity and mobility ("Applications of Nano-Catalyst in New Era," 2012). Organic nanoparticle synthesis using plants has been extensively studied recently and recognised as a non-toxic and efficient method applicable in the biomedical field. They are even utilized as antifungal and antimicrobial agents due to their enhanced reactivity and adequate small size ("Green Synthesis of Silver Nanoparticles: A Comprehensive Review of Methods, Influencing Factors, and Applications," 2024).

Zoonotic diseases are defined as infections that are transmissible naturally from vertebrates (mainly animals, but also birds, reptiles, and other vertebrates) to humans (Rahman et al., 2020). All known diseases were initially present in animals before finding their way to humans. When the pathogen responsible for the disease originates in an animal, the diseases caused may be termed as zoonoses (Rahman et al., 2020; Vourc'h et al., 2022).

1.2. Importance of Developing Therapeutics for Zoonotic Diseases

Zoonotic diseases greatly affect world health, food security, and economies, particularly in low-income locations where poverty and concurrent outbreaks of several zoonoses intensify their impact (Tsai et al., 2010; Rahman et al., 2020; Vourc'h et al., 2022). These disorders are generally underdiagnosed and undertreated due to a lack of early and quick diagnostic techniques, as well as appropriate therapy alternatives. The discovery of novel medications for zoonotic infections is vital not only to relieve their immediate health consequences but also to minimize their potential to generate pandemics, as witnessed with zoonotic influenza, Ebola, and coronaviruses like SARS and MERS (Bardhan et al., 2023).
Additionally, the growth of antibiotic resistance in zoonotic diseases, particularly in bacterial disorders like anthrax and zoonotic influenza, highlights the requirement for innovative therapies. Outbreaks of zoonotic illnesses offer financial, social, and political issues, needing a proactive strategy to minimize their risks and address the underlying causes. Lately, advanced therapies, especially nanoparticle-based methods, show promise in resolving these problems by strengthening targeted drug delivery, improving effectiveness, and lowering resistance, effectively paving the path for improved management of emergent and established zoonoses (Cheng et al., 2023; "The Impacts of Animal Agriculture on One Health—Bacterial Zoonosis, Antimicrobial Resistance, and beyond," 2024).

2. Nanoparticles in Biomedical Applications

Nanoparticles have drawn a lot of interest in the field of biomedicine because of their distinct physical, chemical, and biological characteristics (Wang & Wang, 2014). Drug delivery, imaging, and diagnostics are just a few of the biomedical uses for these particles, which are usually between 1 and 100 nanometres in size (Sim & Wong, 2021). Because of their tiny size, they can interact at the molecular level with biological systems, which makes them extremely effective and adaptable in improving therapeutic results, but using them also has drawbacks in terms of toxicity, safety, and regulatory obstacles (Abbasi et al., 2023).

2.1. Types of Nanoparticles Used in Biomedicine

Depending on their shape and content, many kinds of nanoparticles are used in biomedical applications, each with unique benefits. Most often utilized nanoparticles are depicted in Fig. 1.

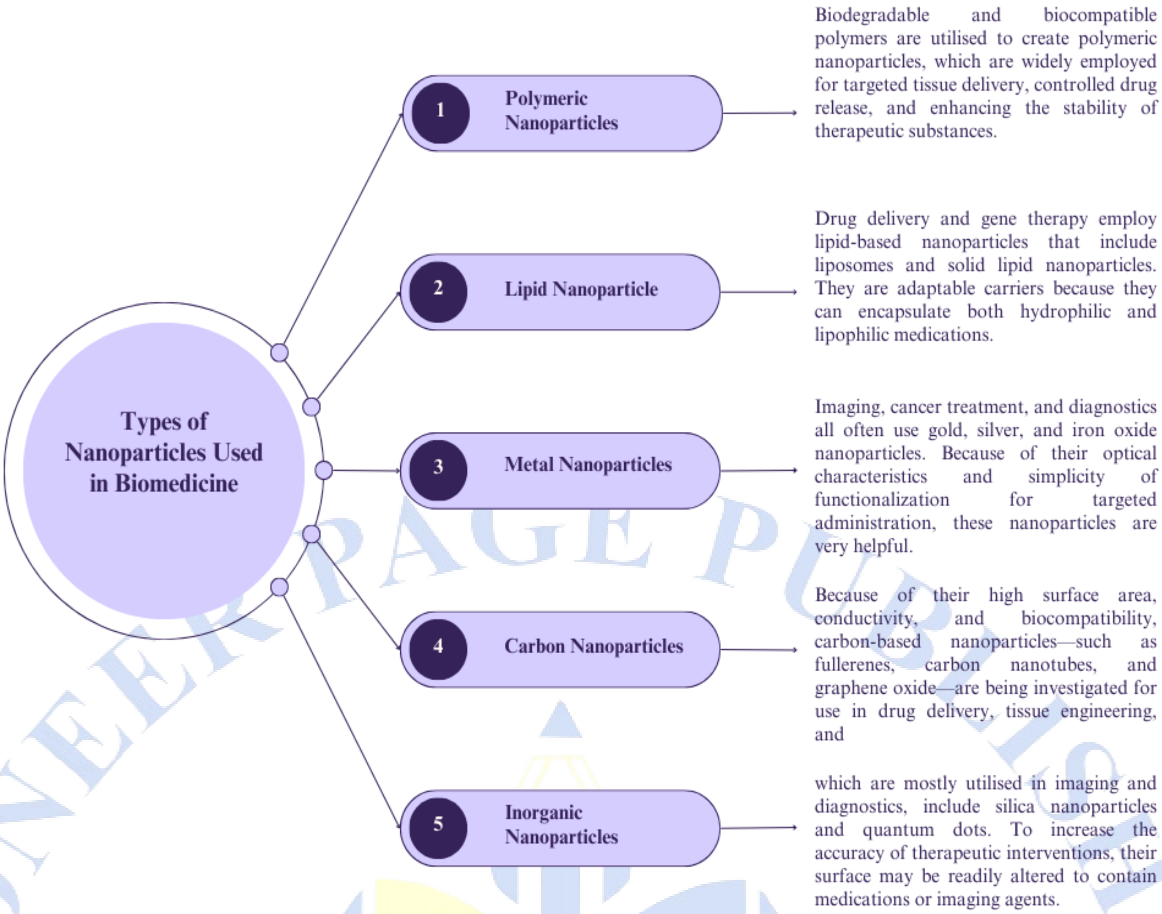

Fig. 1: Types of Nanoparticles used in Biomedicine (McNamara & Tofail, 2016)

2.2. Advantages

Targeted Drug Delivery: By delivering medications straight to the site of disease, nanoparticles may be designed to target certain cells or tissues, minimising adverse effects and enhancing therapeutic efficiency (Patra et al., 2018; Yetisgin et al., 2020; Manzari et al., 2021).

Bioavailability: Nanoparticles' tiny size enhances their solubility and surface area, which improves the bioavailability of medications that aren't very water soluble (Patra et al., 2018; Harish et al., 2022).

Controlled Release: By enhancing the therapeutic index and lowering the frequency of dose, nanoparticles enable the controlled release of medications over prolonged periods of time (Malhotra & Prakash, 2014).

Decreased Toxicity: Drugs can be delivered with nanoparticles in a targeted way, reducing systemic toxicity by releasing the medication just where it is required (Zhang L et al., 2008).

3. Zoonotic Diseases: Overview and Impact

3.1. Common Zoonotic Diseases and Their Transmission

Numerous pathogens, including bacteria, viruses, and parasites, are responsible for zoonotic illnesses. They can be transmitted by direct contact with diseased animals, contaminated food or water, or vectors like insects. Human behavior, environmental changes, and interactions between domestic animals, wildlife, and people are some of the variables that affect the spread of zoonotic diseases. Preventing outbreaks and protecting public health need an understanding of prevalent zoonotic illnesses and how they spread (Taylor et al., 2001). A detailed list of these illnesses is provided in Table 1, arranged according to the taxonomic categories of viruses, parasites, and bacteria.

Table 1: List of zoonotic diseases caused by various pathogens (Rahman et al., 2020)

Taxonomic Group	Zoonotic Disease	Examples
Bacteria		
	Leprosy	*Mycobacterium leprae*
	Brucellosis	Brucella species (*B. abortus, B. melitensis*)
	Glanders	*Burkholderia mallei*
	Ehrlichiosis	Ehrlichia species *(E. chaffeensis, E. ewingii)*
	Borreliosis	*Borrelia burgdorferi* (Lyme disease)
	Mycoplasmosis	Mycoplasma species (*M. pneumoniae*)
	Anaplasmosis	*Anaplasma phagocytophilum*
	Rabies	Rabies virus (Rabies lyssavirus)
	Anthrax	*Bacillus anthracis*
	Psittacosis	*Chlamydia psittaci*
	Chlamydial Infection	*Chlamydia trachomatis, C. psittaci*
Parasites		
	Leishmaniasis	Leishmania species
	Toxoplasmosis	*Toxoplasma gondii*
	Cryptosporidiosis	Cryptosporidium species
	Zoonosis	General term for animal-to-human disease transmission
	Giardiasis	*Giardia lamblia*
	Teniasis	Taenia species *(T. solium, T. saginata)*
	Echinococcosis	*Echinococcus granulosus, E. multilocularis*
	Leptospirosis	Leptospira species
	Trypanosomiasis	Trypanosoma species *(T. brucei, T. cruzi)*
	Histoplasmosis	*Histoplasma capsulatum*
	Campylobacteriosis	*Campylobacter jejuni, C. coli*
	Blastomycosis	*Blastomyces dermatitidis*
	Arbovirus Infection	Various arboviruses (West Nile, Dengue, Zika)
	Swine Flu	H1N1 influenza virus
Viruses		
	H1N1 Influenza	H1N1 influenza virus

	H5N1 Avian Influenza	H5N1 influenza virus
	Rabies	Rabies virus (Rabies lyssavirus)
	Lassa Fever	Lassa virus

3.2. Global Impact of Zoonotic Diseases

Zoonotic diseases have a major worldwide influence, impacting not just individual well-being but also the economy, food security, and biodiversity (Rahman et al., 2020). These illnesses account for more than 60% of new infectious diseases in humans, with roughly 75% of them coming from animals (Ellwanger & Chies, 2021). The rising occurrence of zoonotic epidemics has emphasized the interconnection of human, animal, and environmental health, underlining the significance of a One Health strategy to address these concerns (Rahman et al., 2020; Ellwanger & Chies, 2021; Horefti, 2023).

Human Health Impact: Zoonotic diseases represent important public health issues that have elevated morbidity and fatality rates globally (Lin, 2015). Diseases such as rabies, leptospirosis, and brucellosis keep afflicting millions, particularly in low- and middle-income countries where access to healthcare is restricted (Karesh et al., 2012). Emerging zoonotic illnesses like Ebola, SARS, and COVID-19 have created worldwide pandemics, leading to a new strain on healthcare systems. For instance, the COVID-19 pandemic alone resulted in approximately 6 million fatalities globally by 2023 (World Health Organization, 2024).

Economic Consequences: Zoonotic illnesses have terrible economic implications, often impacting worldwide trade, tourist, and agricultural economies. The economic costs from the 2014–2016 Ebola outbreak in West Africa were estimated at $2.8 billion (Huber et al., 2018). Similarly, the COVID-19 epidemic caused an anticipated worldwide GDP reduction of 4.4% in 2020 (Sebbane & Lemaître, 2021; Rezaei, 2024) In addition to direct healthcare expenditures, zoonotic illnesses lead to indirect losses, including diminished labour efficiency and long-term economic recovery issues (Martins et al., 2015).

Food Security and Agriculture: Agricultural systems have become especially vulnerable to zoonotic illnesses, because many of these infections start in cattle. Epidemics such as avian influenza and foot-and-mouth disease affect food production and supply networks, leading to economic losses for farmers and increased food costs for consumers ("Macroeconomic Costs to Large Scale Disruptions of Food Production: The Case of Foot-and-Mouth Disease in the United States," 2012). Moreover, zoonotic infections might limit access to essential animal-source foods, aggravating malnutrition and food insecurity, particularly in developing nations ("The Role of Food Chain in Antimicrobial Resistance Spread and One Health Approach to Reduce Risks," 2023).

Environmental Impact: The transmission of zoonotic diseases is intimately tied to environmental shifts that involve forest loss, urbanisation, and global warming. These conditions promote contacts between humans and wildlife, generating potential for disease spillover (Muehlenbein, 2013). For example, habitat degradation has been related with the spread of viruses like Nipah virus and Hendra virus, both are transferred from bats to humans and cattle (Eaton et al., 2006). Therefore, Measures to maintain biodiversity and safeguard natural ecosystems are vital for lowering the hazards of zoonotic disease emergence ("A Call to Prioritise Prevention: Action Is Needed to Reduce the Risk of Zoonotic Disease Emergence," 2022).

4. Current Approaches to Treating Zoonotic Diseases

4.1. Antibiotics and Antivirals

Zoonotic conditions are often addressed with antibiotics or antivirals, contingent upon the type of infecting microbe. Antibiotic therapy is fundamental for bacterial zoonoses, with prevalent pathogens like Salmonella, Escherichia coli, and Yersinia pestis displaying sensitivity to various antibiotics, which involves fluoroquinolones, tetracyclines, and penicillins (Sebbane & Lemaître, 2021; "A Call to Prioritise Prevention: Action Is Needed to Reduce the Risk of Zoonotic Disease Emergence," 2022; Ponzo et al., 2024). The rising incidence of antibiotic resistance in zoonotic bacteria is a significant issue, complicating treatment alternatives and raising the necessity for cautious antibiotic use in both human and veterinary medicine (Ponzo et al., 2024).

Antiviral therapy for viral zoonoses is scarce, with treatment techniques mostly concentrating on symptom management or the use of specialised antiviral medications for certain diseases. Antiviral drugs like oseltamivir (Tamiflu) are advantageous against influenza viruses, which can be transferred between humans and animals (Cumulated Index Medicus, 1989). Similarly, antiviral medications like ribavirin and favipiravir have been utilised in the therapy of zoonotic viruses such as hantavirus as well as Crimean-Congo hemorrhagic fever virus (Hewson, 2024). Yet the discovery of effective antiviral medications for new zoonotic viruses continues to be a considerable problem, particularly in the setting of unknown and quickly evolving pathogens.

A significant disadvantage of antibiotic and antiviral therapies is their emphasis on treating infections instead of preventing them, stressing need for early identification and prompt intervention techniques. The introduction of new zoonotic diseases, in particular those with pandemic potential, underlines the need for further research into innovative therapeutic strategies, including the creation of broad-spectrum antibiotics and antiviral medicines (Hewson, 2024).

4.2. Vaccines and Immunization Strategies

The prevention of zoonotic diseases, especially those that have a high morbidity and death rate in both human and animal populations, can be achieved most effectively by vaccination. Vaccination programs have been essential in reducing the spread of illnesses such as rabies, bovine TB, and avian influenza (Monath, 2013). In instance, rabies vaccination, both in animals and people, has led to a remarkable drop in human cases globally, indicating the relevance of targeted immunization in reducing zoonotic illnesses ("The Impact of Transmission Dynamics of Rabies Control: Systematic Review," 2019).

For many zoonotic illnesses, however, producing vaccines remains a considerable problem due to the genetic variety of pathogens and the way they can bypass immune responses. This is especially true for emerging zoonotic viruses such as Ebola, Zika, and SARS-CoV-2, for which vaccines are in various stages of development. The quick development of vaccines for SARS-CoV-2, for example, was assisted by modern technologies such as mRNA-based platforms, which might be applied for future zoonotic viruses with comparable genetic traits ("The Impact of Transmission Dynamics of Rabies Control: Systematic Review," 2019; You et al., 2023).

Immunization initiatives for zoonotic illnesses frequently employ a One Health strategy, which combines human, animal, and environmental health factors to limit spread of diseases at the animal-human-environment interface ("The Impact of Transmission Dynamics of Rabies Control: Systematic Review," 2019; You et al., 2023; Zinsstag et al., 2023). To lower the prevalence of zoonotic diseases, policies like wildlife vaccination programs and vector control measures—such as reducing mosquito populations in regions where diseases like dengue and West Nile virus are common—as well as direct animal vaccination are being used more and more. Such integrated methods have shown helpful in limiting the spread of zoonotic infections including Brucella melitensis and Leptospira spp. ("Countering Zoonotic Diseases: Current Scenario and Advances in Diagnostics, Monitoring, Prophylaxis and Therapeutic Strategies," 2024).

5. Nanoparticles as Therapeutic Agents

The intriguing characteristics of NPs, as previously indicated, demonstrate how they interact with pathogens at the molecular level, allowing them to interfere with microbial cellular processes and enhance the effectiveness of medication administration (Wang et al., 2017). This section discusses the mechanisms of action of these nanoparticles in disease therapy and emphasises particular examples of NPs employed in the therapeutic management of zoonotic illnesses.

5.1. Mechanisms of Action of Nanoparticles in Disease Treatment

Nanoparticles display medicinal advantages through different pathways, which might vary based on their dimensions, shape, charge on the surface, and composition (Mohapatra et al., 2018). One of the primary processes includes the direct contact of NPs with microbial cells, resulting in breakdown of the cell membrane. Nanoparticles can permeate the cell membrane due to their tiny size and unique surface features, triggering oxidative stress, membrane damage, and the final death of the pathogen ("Nanoparticles and Their Antimicrobial Properties against Pathogens Including Bacteria, Fungi, Parasites and Viruses," 2018). For instance, silver nanoparticles (AgNPs), which are frequently investigated for their antibacterial characteristics, can create reactive oxygen species (ROS) that destroy microbial DNA, proteins, and lipids, thus affecting cell integrity (Dakal et al., 2016; "Nanoparticles and Their Antimicrobial Properties against Pathogens Including Bacteria, Fungi, Parasites and Viruses," 2018).

Another key factor is the potential of nanoparticles to carry therapeutic compounds straight to the site of infection, hence improving the bioavailability and effectiveness of medications. The large surface area of NPs enables for the loading of various drugs, such as antibiotics or antiviral medicines, which may be progressively released in a controlled way at the place of infection (Dakal et al., 2016; "Nanoparticles and Their Antimicrobial Properties against Pathogens Including Bacteria, Fungi, Parasites and Viruses," 2018; "Nanoparticle Drug Conjugates Treating Microbial and Viral Infections: A Review," 2021). This regulated release lowers systemic negative effects while boosting local therapeutic concentration of medicines. Additionally, nanoparticles may be designed to carry targeting ligands, like antibodies or peptides, which allow the precise attachment of the NPs to infected cells, further increasing treatment specificity and minimizing adverse reactions ("Current Applications of Nanoparticles in Infectious Diseases," 2016).

Nanoparticles also display the potential to alter the immune response. By collaborating with cells of the immune system, like macrophages and dendritic cells. They can boost both innate and adaptive immunity, facilitating the clearance of infections ("Current Applications of Nanoparticles in Infectious Diseases," 2016; "Biomedical Nanoparticle Design: What We Can Learn from Viruses," 2021). This immune modulation has many possible applications in immunotherapy, specifically in the management of viral zoonoses, where increasing the host's immune response might help to limit viral reproduction and spread.

Moreover, certain nanoparticles demonstrate a synergistic impact when paired with traditional antibiotics, which can minimize the probability of acquiring antibiotic resistance. They are useful supplements for the management of multidrug-resistant zoonotic infections because of their capacity to enhance the permeability of bacterial cell walls or disrupt the development of biofilms, which intensifies the effects of antibiotics (Araújo et al., 2024).

5.2. Examples of Nanoparticles Used in Zoonotic Disease Therapeutics

Although the use of nanoparticles to treat zoonotic illnesses remains to be in its early phases, there are a number of encouraging cases that show how effective they can be. For example, silver nanoparticles (AgNPs) are extensively researched for their antibacterial properties against a wide range of pathogens, including those that cause zoonotic diseases including Escherichia coli, Salmonella spp., and Yersinia pestis (Farouk et al., 2020). Silver nanoparticles (AgNPs) have demonstrated the ability to break bacterial cell membranes, impede biofilm formation, and generate oxidative stress, rendering them effective against bacterial infections in humans and animals (Farouk et al., 2020; Tripathi & Goshisht, 2022).

Besides bacterial infections, nanoparticles have been examined for their antiviral capabilities too. Lipid-based nanoparticles have been investigated for their capacity to encapsulate and transport antiviral medicines targeting viral zoonoses, including the rabies virus and the H5N1 avian influenza virus (Farouk et al., 2020; Rai & Yadav, 2022; Tripathi & Goshisht, 2022). These lipid nanoparticles enable the encapsulation of hydrophobic medicines, so amplifying their stability and boosting cellular uptake (Xu et al., 2022). In example, lipid nanoparticles have played a crucial role in the creation of mRNA-based vaccines, such as those utilised in the fight against SARS-CoV-2, highlighting their possibilities for the treatment of zoonotic viral illnesses ("mRNA Vaccines against Infectious Diseases and Future Direction," 2024).

Gold nanoparticles (AuNPs) are a distinct category. These nanoparticles are perfect for targeted drug administration and diagnostics since they are easily functionalised with a variety of biomolecules. In the context of viral zoonoses, AuNPs have been studied for their potential in administering antiviral medicines and boosting the immune response to viral infections, including Zika virus and Ebola virus (Minakshi et al., 2020). AuNPs have shown the capacity to engage with viral particles, obstructing their binding to host cells and so impeding the viral entrance process ("DNA-AuNP Networks on Cell Membranes as a Protective Barrier to Inhibit Viral Attachment, Entry and Budding," 2016).

The potential applications of magnetic nanoparticles (MNPs) in zoonotic disease detection and treatment are being investigated too. Due to their magnetic features, MNPs can be targeted to specific locations of infection via external magnetic fields, increasing the localized administration of therapeutic medicines ("Magnetic Nanoparticles for Theragnostics, 2009; "DNA-AuNP Networks on Cell Membranes as a Protective Barrier to Inhibit Viral Attachment, Entry and Budding, 2016"). Additionally, MNPs can be packed with antibiotics or employed in hyperthermia therapies, where they emit targeted heat upon exposure to an oscillating magnetic field, resulting in the killing of pathogen cells.

Moreover, silica nanoparticles (SiNPs) have attracted interest due to their biocompatibility and capacity to carry a range of medications, such as antibiotics and antimalarials ("Magnetic Nanoparticles for Theragnostics," 2009; "DNA-AuNP Networks on Cell Membranes as a Protective Barrier to Inhibit Viral Attachment, Entry and Budding," 2016; Kothawade & Pande, 2024). These NPs can be functionalized to enhance the specificity of drug delivery, increasing the results of therapy for zoonotic diseases including malaria, caused by Plasmodium spp., and other parasite infections (Kothawade & Pande, 2024).

5.3. Ongoing Clinical Trials and Promising Results

One of the most significant uses of nanoparticles in zoonotic therapeutics is in the creation of nanoparticle-based vaccinations and antiviral medicines. As an example, in the scenario of the Ebola virus, nanoparticles are being employed to deliver RNA vaccines (Sumira Malik et al., 2023). The nanoscale formulation of the vaccine can boost its stability and improve immunological responses by imitating the viral structure, thereby permitting a more effective presentation to the immune system (Chattopadhyay et al., 2017; Sumira Malik et al., 2023). In clinical studies, these nanoparticle-based vaccinations have demonstrated promising outcomes, notably in terms of heightened immune protection with decreased adverse effects (Chattopadhyay et al., 2017; Bezbaruah et al., 2022; Sumira Malik et al., 2023).

Furthermore, for bacterial zoonoses like Brucella spp., nanoparticle-based solutions are currently being researched to target the pathogens more efficiently ("Nano and Microparticle Drug Delivery Systems for the Treatment of Brucella Infections," 2023). NPs can operate as carriers for antimicrobial agents, providing a more regulated release and minimizing the probability of resistance ("Solid Nanoparticles for Oral Antimicrobial Drug Delivery: A Review," 2019). Preliminary evidence from clinical studies show that these formulations may offer a unique way to manage chronic infections that are difficult to control with traditional antibiotics.

In the context of parasitic zoonoses, like Leishmania and Trypanosoma, nanomaterials have been utilized as carriers of drugs to address the hurdles associated with low solubility and toxicity of conventional therapies (Vaghela et al., 2019). Clinical studies are presently underway to examine the safety and efficacy of liposomal formulations and gold nanoparticles in enhancing the pharmacokinetics of antiprotozoal medicines ("Recent Advances in Nanomedicines for the Treatment of Global Infectious Diseases," 2024). Early-phase experiments demonstrate that these nanoparticles can successfully target infected cells while limiting systemic negative effects.

Despite the optimistic findings of these current trials, significant hurdles remain. The biocompatibility and toxicity of nanoparticles are of key concern, particularly in the long-term usage of medicines. As nanoparticles interact with biological systems, their potential to trigger immunological responses, inflammatory reactions, or organ damage must be carefully examined. To address these problems, researchers are focused on the construction of biocompatible nanoparticles with tailored delivery methods to limit detrimental effects ("Biocompatibility of Engineered Nanoparticles for Drug Delivery," 2013; "Recent Advances in Nanomedicines for the Treatment of Global Infectious Diseases," 2024),

6. Challenges and Ethical Implications

The potential use of nanoparticles in disease therapy, while promising, involves important ethical problems that must be addressed to enable responsible research and implementation of nanoparticle-based therapeutics. Ethical challenges encompass a wide variety of topics, from issues related to safety and informed consent to larger social implications. Given the evolving nature of nanotechnology, continual conversation between academics, politicians, and the public is vital to manage these ethical difficulties (Desai, 2012).

- **Safety and Long-term Effects**

One of the key ethical problems in nanoparticle-based treatments is their safety, particularly considering the unique biological interactions of nanoparticles in comparison to traditional medications. The tiny size, vast surface area, and surface reactivity of nanoparticles might lead to unanticipated toxicities, such as immune system activation, inflammatory reactions, or organ-specific accumulation (Wadhawan et al., 2024). These potential hazards are heightened by the fact that long-term investigations on the bioaccumulation and toxicity of nanoparticles in humans are yet lacking. From an ethical stance, guaranteeing the safety of patients via thorough preclinical and clinical testing is crucial, and any therapeutic intervention should emphasise limiting harm while enhancing possible benefit (Kumarasamy et al., 2024).

- **Informed Consent and Patient Autonomy**

In clinical studies employing nanoparticles, gaining informed permission is a critical ethical need. Patients must be fully informed of the experimental nature of nanoparticle-based therapy, including any possible dangers that have not yet been completely documented. Given the intricacy of nanoparticle technology, it is vital that participants in clinical trials are supplied with clear and accessible information regarding the treatment's processes, uncertainties, and probable adverse effects (Ioannidis et al., 2018; Isibor, 2024). Informed consent becomes even more hard when dealing with nanoparticle-based therapies for vulnerable groups, such as children or those with damaged health, when their capacity to make autonomous decisions may be reduced.

- **Privacy and Data Security**

The use of nanoparticles in illness therapy also poses privacy concerns, particularly if nanoparticles are intended to follow disease biomarkers or carry medications directly to specific organs (Ioannidis et al., 2018; Alghamdi et al., 2022; Isibor, 2024). Nanotechnology-based diagnostic technologies may require the collecting of sensitive health data, which, if not adequately handled, might expose patients to privacy problems. Ensuring the security of patient information and protecting against data breaches is a crucial ethical obligation (Verma et al., 2024).

- **Environmental Impact**

Another ethical dilemma emerges from the possible environmental dangers of nanoparticles, especially those utilised in large-scale manufacture for medicinal purposes. The extensive usage of nanoparticles may lead to environmental pollution, since these particles might aggregate in ecosystems, which could result in ecological damage or disrupting biodiversity (Zhang et al., 2018). Ethical problems about the environmental destiny of nanoparticles need the development of eco-friendly, biodegradable materials to reduce their influence once they have been utilised in medicinal therapies (Zhang et al., 2018; Bellanthudawa et al., 2023). Researchers and producers must balance the advantages of nanoparticle-based medicines with their environmental impact, so their development does not lead to unintended harm to ecosystems.

- **Equity and Access to Treatment**

As nanoparticle-based medicines offer the promise to change therapy for many infectious and chronic illnesses, concerns around fair access to these medications must be addressed. Advanced nanoparticle formulations may be costly to develop, raising problems regarding their availability in low-resource contexts (Zhang et al., 2018; Euliano et al., 2022; Bellanthudawa et al., 2023). Ensuring that these innovative medicines are available to marginalised groups is an ethical necessity, especially when addressing the worldwide inequities in healthcare access. Policymakers and healthcare professionals must work to make nanoparticle-based medicines readily available to all populations, irrespective of their socio-economic background (Akram, 2024).

- **Social and Cultural Considerations**

Nanoparticles' potential to affect biological systems at the molecular level might be regarded as interfering with the natural path of life, causing problems among specific cultural and religious groups. The use of nanoparticles in gene therapy or changing immune responses may be considered as controversial, particularly when these treatments violate conventional views about the human body or the sanctity of life. Public participation and clear communication regarding the ethical implications of such treatments are crucial to eliciting public trust and establishing social acceptance of nanoparticle-based therapeutics (Bottini et al., 2011).

Conclusion

In conclusion, nanoparticle-based treatments have emerged as a new method for combating some of the most detrimental zoonotic and infectious illnesses in the modern era. Their capacity to optimize medication distribution, improve bioavailability, target specific cells or tissues, and lessen negative consequences makes them a compelling alternative to established therapeutic approaches. Ongoing clinical trials and preclinical research emphasize the adaptability and promise of nanoparticles in treating a wide array of illnesses caused by viruses, bacteria, and parasites. Despite these breakthroughs, major problems remain, notably regarding the safety, long-term impacts, and ethical implications of nanoparticle therapeutics. Consequently, even though nanoparticles have an undisputed potential to fight zoonotic illnesses, their development must be handled carefully, with a focus on thorough safety evaluations and ethical concerns.

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