Available online at www.worldscientificnews.com

World Scientific News

An International Scientific Journal

WSN 201 (2025) 1-14 EISSN 2392-2192

Applications of Nanotechnology in the Therapy of Inflammatory Diseases

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ABSTRACT

Inflammatory diseases, including cancer, hypertension, and inflammatory bowel disease (IBD), pose significant challenges in modern medicine due to limitations associated with conventional therapies, such as low bioavailability, systemic side effects, and inadequate targeting of diseased tissues. Nanotechnology has emerged as a promising solution to these challenges, offering innovative drug delivery systems that enhance therapeutic efficacy while minimizing adverse effects. In cancer treatment, nanoparticles facilitate targeted drug delivery, improve chemotherapeutic retention in tumors, and enhance radiation therapy, thereby reducing damage to healthy tissues. Additionally, nanotechnology enables the development of immunotherapeutic strategies, including nanoparticle-based vaccines that stimulate the immune system to recognize and eliminate cancer cells. In hypertension management, nanoformulations, such as nanoemulsions, solid lipid nanoparticles, and dendrimers, improve the solubility and bioavailability of antihypertensive drugs, leading to enhanced therapeutic outcomes and sustained drug release. Similarly, in IBD, nanocarrier-based systems allow for localized drug delivery to inflamed intestinal tissues, reducing systemic absorption and improving treatment precision.

The primary objective of nanoformulations is to optimize drug delivery by increasing bioavailability, targeting specific disease sites, and reducing adverse effects. As research continues to advance, nanotechnology-based therapies are expected to revolutionize the treatment of inflammatory diseases by offering safer, more effective, and long-lasting treatment options. These innovations hold great potential for improving patient outcomes and transforming the future of medicine.

(Received 10 January 2025; Accepted 20 February 2025; Date of Publication 4 March 2025)

***Keywords*:** Nanotechnology, Inflammatory diseases, Cancer, Nanoparticles, Disease therapy

1. INTRODUCTION

Nanotechnology is the study and application of materials and devices at the nanoscale, typically ranging from 1 to 100 nanometers. The term "nano" originates from the Greek word for "dwarf," highlighting the manipulation of materials at an atomic and molecular level (Laroui et al., 2013; Haleema et al., 2023). To provide context, a nanometer is one-billionth of a meter; for comparison, the DNA double helix measures approximately 2 nm in diameter, while the smallest bacteria are around 200 nm (De Jong and Borm, 2008). The ability to manipulate materials at this scale results in unique physicochemical properties, including enhanced electrical conductivity, chemical reactivity, magnetism, and optical effects, which significantly differ from those of bulk materials due to size-dependent quantum phenomena (Nikalje, 2015; Haleema et al., 2023). These nanoscale modifications enable the development of advanced materials with improved functionality, making nanotechnology a transformative field with broad applications across various disciplines, particularly in medicine.

Nanotechnology is employed using two primary approaches. The top-down approach involves reducing larger structures to the nanoscale, a technique widely used in nanoelectronics and nanoengineering. Conversely, the bottom-up approach involves assembling nanostructures at the atomic or molecular level, mimicking biological and chemical self-assembly processes (Haleema et al., 2023). Both approaches have significantly advanced medical applications, particularly in drug delivery, diagnostics, and therapeutic interventions.

In recent years, nanotechnology has revolutionized the treatment of inflammatory diseases by enabling targeted drug delivery, reducing systemic toxicity, and improving bioavailability. Inflammatory diseases, such as rheumatoid arthritis, inflammatory bowel disease, and multiple sclerosis, present significant treatment challenges due to the complexity of immune dysregulation and the adverse effects of conventional therapies. The advent of nanomedicine has facilitated the development of biocompatible drug carriers, nanoparticle-based anti-inflammatory agents, and precision-targeted therapies that enhance treatment efficacy while minimizing side effects (Laroui et al., 2013; De Jong and Borm, 2008).

Despite numerous advancements, challenges remain in translating nanotechnology-based therapies from research to clinical practice, including safety concerns, regulatory hurdles, and large-scale manufacturing limitations. This review aims to provide a comprehensive analysis of the therapeutic applications of nanotechnology in inflammatory diseases by discussing the mechanisms through which nanoparticles exert their effects, evaluating recent advancements in nanomedicine, and highlighting the challenges associated with clinical translation. By synthesizing current knowledge and emerging trends, this paper offers insights into the potential of nanotechnology to reshape the landscape of inflammatory disease management.

2. HISTORIC DEVELOPMENT OF NANOTECHNOLOGY

The concept of nanotechnology was first introduced by physicist Richard Feynman in 1959 during his iconic lecture, "There's Plenty of Room at the Bottom." In this lecture, Feynman envisioned the possibility of manipulating individual atoms to create new structures and materials, laying the theoretical foundation for the field (Nikalje, 2015; Haleema et al., 2023). However, it was not until 1974 that the term "nanotechnology" was formally introduced by Norio Taniguchi, who defined it as the precise engineering of materials at the nanoscale (Nikalje, 2015).

The field gained significant momentum in the 1980s, largely due to the pioneering work of K. Eric Drexler. In 1986, Drexler published "*Engines of Creation: The Coming Era of Nanotechnology,"* where he proposed the concept of nanoscale "assemblers" capable of constructing complex structures atom by atom. That same year, he co-founded The Foresight Institute to promote public awareness and advance the study of nanotechnology (Wolfram, 2002).

The following decade saw transformative discoveries that shifted nanotechnology from theoretical speculation to a rapidly growing scientific discipline. One of the most notable breakthroughs occurred in 1991 when S. Iijima discovered carbon nanotubes, a finding that revolutionized material science and paved the way for numerous applications in medicine, electronics, and engineering. By the late 1990s, nanomedicine had emerged as a distinct field with the publication of *Nanomedicine* by R. Freitas in 1999, highlighting the potential of nanotechnology in healthcare and disease management. Recognizing its growing importance, governments around the world began prioritizing nanotechnology research. In 2000, the establishment of the National Nanotechnology Initiative (NNI) provided a structured framework for funding and strategic direction, accelerating the development and commercialization of nanotechnology-based innovations (Wolfram, 2002).

Between 2001 and 2004, advancements in molecular modeling, DNA-based self-assembly, and protein structure design were recognized with the prestigious Feynman Prize in Nanotechnology. These developments further cemented the interdisciplinary nature of nanotechnology, integrating principles from physics, chemistry, biology, and engineering. The period from 2005 to 2010 marked the emergence of three-dimensional nanosystems, leading to breakthroughs in robotics, 3D networking, and the creation of dynamic nanoproducts capable of adaptive state changes. By 2011, molecular nanotechnology had firmly established itself as a critical field of research, expanding its applications beyond medicine into electronics, energy storage, and environmental science (Nikalje, 2015).

Through these milestones, nanotechnology has evolved from a visionary idea into a transformative discipline with widespread applications. The continuous refinement of nanoscale engineering techniques and the integration of nanotechnology across multiple scientific fields underscore its potential to address complex global challenges and drive innovation in the years to come.

3. NANOPARTICLES

Nanoparticles (NPs) are materials that exist within the nanometric scale, typically ranging from 1 to 100 nanometers. Their unique physicochemical properties distinguish them from bulk materials, with characteristics governed by quantum mechanics rather than classical physics. The method of synthesis plays a crucial role in determining their behavior and applications, with two main approaches: the bottom-up method, which builds structures atom by atom through chemical processes, allowing precise control over particle size, and the top-down method, which involves breaking down bulk materials into smaller particles, often leading to a broader size distribution (Polizu et al., 2006; Ren et al., 2021).

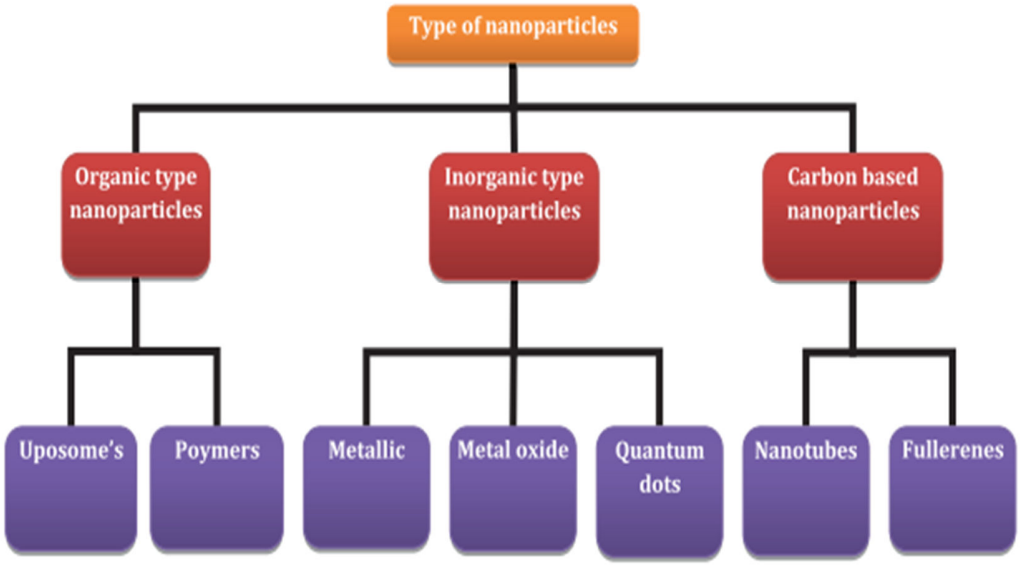

Figure 1. Classification of Nanoparticles (Haleema et al., 2023)

Size and Medical Implementation

The size of nanoparticles significantly influences their interaction with biological systems. While nanoparticles are conventionally defined as being between 1 and 100 nanometers, their medical applications often extend this range up to 1000 nanometers (1 micrometer). This size range is particularly relevant to cellular uptake, as nanoparticles within this limit can penetrate non-phagocytic eukaryotic cells, whereas larger particles—up to 4 micrometers—are internalized predominantly by phagocytic immune cells such as macrophages (Lacoeuille et al., 2007; Tabata et al., 1996; Ren et al., 2021). Particles exceeding 1000 nanometers are classified as microparticles and exhibit different physiological behaviors compared to their nanoscale counterparts.

Unique Physicochemical Properties

Nanoparticles possess distinct properties that make them valuable across multiple disciplines, particularly in biomedical applications. One of their most significant attributes is their high surface area-to-mass ratio, which enhances their ability to bind, absorb, and transport various compounds, including drugs, proteins, and molecular probes. This property makes nanoparticles particularly effective in targeted drug delivery and diagnostic imaging (Polizu et al., 2006; Tamura et al., 2006; Laroui et al., 2011). Additionally, nanoparticles exhibit dynamic motion in liquid media due to Brownian motion, facilitating their interaction with cells and biological membranes.

Composition and Functionalization

Nanoparticles are composed of either biological or synthetic materials, which influence their stability, biocompatibility, and functionality. Biological nanoparticles, such as those made from lipids, chitosan, or albumin, are often biodegradable and suitable for medical applications, whereas synthetic nanoparticles, such as polymeric, metallic, carbon-based, or silica nanoparticles, offer greater structural stability and tunability.

Surface properties play a vital role in determining their biological interactions. Surface charge, for example, influences cellular uptake and biodistribution—positively charged nanoparticles tend to adhere to healthy epithelial tissues, while negatively charged nanoparticles exhibit increased affinity for inflamed mucosal surfaces (Jung et al., 2000; Jubeh et al., 2004). Additionally, hydrophilic coatings enhance nanoparticle penetration through biological barriers, while porous structures facilitate the encapsulation and sustained release of therapeutic agents (Sant et al., 2005).

To enhance their biocompatibility and circulation time, nanoparticles are often functionalized with surface modifications such as polyethylene glycol (PEG) coatings, which reduce immune recognition and enzymatic degradation (Niidome et al., 2006; Tobio et al., 2000). Functionalization with polymers, antibodies, or ligands further improves targeting capabilities, enabling nanoparticles to deliver therapeutic agents with high precision to specific cells or tissues.

Influence of Shape on Biological Performance

The shape of nanoparticles plays a crucial role in their biological interactions and effectiveness. Spherical nanoparticles, such as liposomes, are among the most widely studied due to their ease of fabrication, stability, and efficient drug encapsulation. However, advancements in nanotechnology have enabled the development of non-spherical designs, including disk-shaped and rod-shaped nanoparticles, which have demonstrated improved adhesion and multivalent interactions with biological surfaces.

Despite their potential benefits, certain nanocrystalline structures may pose safety concerns. For instance, α-quartz silica nanoparticles have been found to induce pro-inflammatory effects due to lysosomal rupture, highlighting the need for careful material selection in biomedical applications (Hornung et al., 2008; Huang et al., 2018).

Nanoscale and Nanostructures

The nanoscale represents the dimensional range at which material properties, such as electrical conductivity and optical characteristics, are fundamentally determined. Nanomaterials, which encompass both nanocrystalline and nanostructured materials, are integral to pharmaceutical and biomedical applications. Different nanostructures, including nanoparticles, dendrimers, micelles, drug conjugates, and metallic nanoparticles, offer distinct advantages based on their composition and functionality (Polizu et al., 2006; Boisseau and Loubaton 2011).

Among the most extensively developed nanocarriers for targeted drug delivery are liposomes, which are spherical vesicles ranging from 50 to 200 nanometers. Formed when dry phospholipids are hydrated, liposomes provide a biocompatible system for encapsulating drugs, genes, proteins, and peptides. Their versatility, stability, and efficient drug entrapment make them ideal for long-circulating therapeutic applications (Nikalje 2015).

Dendrimers, another class of nanostructures, are highly branched, tree-like molecules that typically measure less than 10 nanometers in size. Their unique architecture, consisting of a core, branching units, and a densely packed surface, makes them particularly effective for controlled and targeted drug delivery. Their internal cavities can encapsulate bioactive compounds, facilitating precision medicine approaches, particularly in targeting macrophages and liver cells (Polizu et al., 2006).

Among inorganic nanomaterials, carbon nanotubes have gained prominence due to their unique structural and mechanical properties. These hollow, cylindrical molecules allow for the encapsulation and transport of therapeutic agents while also offering exceptional mechanical strength and electrical conductivity (Wolfram, 2002; Nikalje, 2015). Similarly, metallic nanoparticles, particularly those composed of silver and gold, have found extensive applications in drug delivery and biosensing. Their high surface-to-volume ratio and functionalization potential enable precise targeting, enhancing therapeutic efficacy, particularly in cancer treatment (Wolfram, 2002; Nikalje, 2015).

4. CLASSIFICATION OF NANOMATERIALS

Nanomaterials can be classified based on their dimensionality and phase composition, each of which influences their properties and potential applications in medicine. Understanding these classifications is crucial for optimizing their use in drug delivery, diagnostics, and therapeutic interventions.

In terms of dimensionality, nanomaterials are broadly categorized into one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures. One-dimensional nanomaterials, such as nanorods and nanowires, have one dimension within the nanoscale range, typically less than 100 nanometers, while their other dimensions extend beyond this limit. These structures have shown great promise in biomedical imaging, biosensing, and targeted drug delivery due to their high aspect ratio and surface reactivity. For example, gold nanorods have been extensively studied for their photothermal properties, allowing for controlled heating of targeted cells in cancer therapy (Wolfram, 2002; Polizu et al., 2006).

Two-dimensional nanomaterials, including nanotubes, nanofibers, and nanoplates, have two dimensions confined within the nanoscale range.

Carbon nanotubes, a prominent example, have garnered attention for their exceptional mechanical strength, electrical conductivity, and drug-loading capacity. Their ability to penetrate cell membranes with minimal cytotoxicity makes them suitable for gene therapy and intracellular drug delivery. In contrast, nanofibers, often composed of polymers or peptides, have been widely used in tissue engineering and regenerative medicine to mimic extracellular matrices and promote cell adhesion and growth (Polizu et al., 2006; Nikalje, 2015).

Three-dimensional nanomaterials, such as nanoparticles, quantum dots, and nanospheres, exhibit all three dimensions at the nanoscale. Among these, metallic nanoparticles—especially gold and silver nanoparticles—have been widely explored for their antimicrobial properties, targeted drug delivery, and biosensing applications. Quantum dots, semiconductor nanocrystals with unique optical properties, have revolutionized molecular imaging and early cancer diagnostics due to their ability to fluoresce in different colors based on size and composition. Liposomal nanoparticles, which form lipid bilayer vesicles, have become one of the most effective drug carriers in chemotherapy and vaccine delivery, owing to their biocompatibility and ability to encapsulate hydrophilic and hydrophobic drugs (Nikalje, 2015; Haleema et al., 2023).

Beyond dimensional classification, nanomaterials can also be categorized based on their phase composition, distinguishing between single-phase and multi-phase systems. Single-phase nanomaterials consist of a uniform composition and can be either crystalline or amorphous. These materials include monolithic nanoparticles, nanolayers, and nanocoatings, which are often used in biomedical implants and antimicrobial surface coatings to prevent infections. Multi-phase nanomaterials, on the other hand, combine different phases to enhance their mechanical, chemical, or biological properties. These include matrix nanocomposites, core-shell nanoparticles, and hybrid nanostructures, which have been extensively developed for controlled drug release and targeted therapy. For example, core-shell nanoparticles consisting of a polymeric shell and a metallic or magnetic core have been engineered for magnetic resonance imaging (MRI) contrast enhancement and targeted drug delivery, allowing for real-time tracking of therapeutic agents within the body (Nikalje, 2015; Haleema et al., 2023).

Additionally, more complex multi-phase systems, such as colloidal dispersions, aerogels, and ferrofluids, incorporate nanoscale components in diverse configurations. Colloidal nanoparticles, including micelles and dendrimers, play a significant role in nanomedicine by improving the solubility and bioavailability of poorly soluble drugs. Aerogels, known for their high porosity and lightweight structure, have been investigated for their potential in drug adsorption and sustained release. Ferrofluids, which contain magnetic nanoparticles suspended in a liquid carrier, have been explored for hyperthermia treatments, where localized heating is applied to tumor cells under an external magnetic field, leading to cancer cell destruction with minimal damage to surrounding tissues (Polizu et al., 2006; Boisseau and Loubaton, 2011).

5. APPLICATION OF NANOTECHNOLOGY

The ability to manipulate and observe materials at the nanoscale has opened up a broad spectrum of possibilities across multiple scientific and industrial sectors. Nanotechnology, which enables precise control of materials at the atomic and molecular levels, has been particularly transformative in healthcare, medicine, and drug delivery.

Health and Medicine

Nanomedicine, an emerging field that integrates nanotechnology with healthcare, has revolutionized the way biological molecules interact at the nanoscale. By leveraging nanomaterials and nanoelectronic biosensors, this field enhances diagnostics, treatment, and disease prevention. The distinct physical and chemical properties of nanodevices contribute to their increased sensitivity and efficiency in medical applications (Nikalje, 2015).

Many applications of nanomedicine have progressed from laboratory research to animal models and are now advancing toward human clinical trials. For instance, gold nanoshells are being investigated for their potential in cancer diagnosis and therapy, while liposomal nanoparticles are widely used as vaccine adjuvants and drug carriers (Boisseau & Loubaton, 2011). Additionally, nanotechnology has been successfully applied in drug detoxification studies in rats, demonstrating its potential for medical interventions. The development of smaller, minimally invasive medical devices with faster biochemical reaction times further underscores the advancements in nanomedicine (LaVan et al., 2003).

Nanotechnology has also played a significant role in addressing complex diseases, including cancer, diabetes, Alzheimer's disease, Parkinson's disease, cardiovascular disorders, and infectious diseases such as HIV. By enabling early detection, precise diagnosis, and targeted treatment, nanomedicine has improved disease management strategies. For example, gold nanoparticles tagged with DNA segments have facilitated efficient gene sequencing and the early detection of genetic disorders (LaVan et al., 2003; Boisseau & Loubaton, 2011).

Drug Delivery

The use of nanoparticles in drug delivery has significantly improved therapeutic efficiency by ensuring that drugs are precisely targeted to specific sites, thereby minimizing side effects and optimizing treatment outcomes. Various nanoparticle systems, including dendrimers and nanoporous materials, have been developed to enhance drug delivery. Additionally, micelles formed from block copolymers encapsulate and transport drugs to designated locations, while nanoelectromechanical systems facilitate controlled drug release. In cancer therapy, iron nanoparticles and gold nanoshells are being explored for targeted treatments, which not only enhance treatment precision but also reduce drug consumption and associated costs (LaVan et al., 2003; Cavalcanti et al., 2008).

Advancements in nanotechnology have also paved the way for molecularly engineered drug delivery systems, such as nanorobots, which allow for highly precise targeting and controlled drug release at the cellular level (Cavalcanti et al., 2008). Furthermore, nanoparticles serve as contrast agents in medical imaging techniques such as ultrasound and MRI, improving diagnostic accuracy. Self-assembled biocompatible nanodevices are also being developed to autonomously detect and treat cancer cells, offering new possibilities for non-invasive therapeutic approaches (Nikalje, 2015; Haleema et al., 2023).

Nanotechnology has also enhanced pharmacological and therapeutic properties through the development of lipid- and polymer-based nanoparticles, which improve drug bioavailability and distribution. These systems enable drugs to bypass the body's natural defense mechanisms, thereby increasing treatment efficiency (Bertrand & Leroux, 2012; Haleema et al., 2023).

Additionally, innovative drug delivery mechanisms, such as triggered responses, ensure that drugs activate only in the presence of specific biological signals. Nanoparticles have also been utilized to enhance drug solubility and regulate release rates, reducing toxicity and increasing treatment effectiveness (Nagy et al., 2012).

Despite the promising advancements in nanomedicine and targeted drug delivery, challenges remain, particularly regarding the biodistribution and potential toxicity of nanoparticles. Ongoing research seeks to optimize these systems to ensure their safety and efficacy in medical applications. For instance, studies in mice have shown that the charge of nanoparticles influences their excretion pathways—positively charged gold nanoparticles are excreted via the kidneys, whereas negatively charged ones tend to accumulate in organs such as the spleen and liver (Minchin, 2008).

In summary, nanotechnology has introduced groundbreaking innovations in healthcare, drug delivery, and medical diagnostics. As research continues to refine and optimize these applications, nanomedicine holds immense potential to revolutionize disease treatment, improve patient outcomes, and contribute to the advancement of precision medicine.

6. TREATMENT OF INFLAMMATORY DISEASES

Nanotechnology is emerging as a promising approach in the treatment of various inflammatory diseases, including cancer, hypertension, and inflammatory bowel diseases. By enhancing drug delivery, reducing side effects, and improving therapeutic efficacy, nanotechnology-based treatments offer significant advantages over traditional therapies.

Cancer

Conventional cancer treatments, such as surgery, radiation, and chemotherapy, often cause damage to healthy tissues or fail to eliminate all cancer cells. Nanotechnology presents an innovative approach by enabling precise drug delivery to tumor sites, improving surgical tumor resection, and enhancing the effectiveness of radiation therapy. These advancements reduce risks for patients and improve survival outcomes (Malik et al., 2023; Haleema et al., 2023).

A key advantage of nanotechnology in cancer therapy is its ability to target specific cancer cells while minimizing harm to surrounding tissues. For instance, nanoparticles can function as hyperthermia agents, generating localized heat to destroy tumor cells when exposed to external stimuli such as magnetic fields, X-rays, or light. Additionally, nanoparticles facilitate the targeted delivery of chemotherapy drugs or gene therapies, thereby improving drug efficacy and reducing systemic side effects (Malik et al., 2023).

Researchers are also exploring nanoparticles for the delivery of immunotherapies, such as immunostimulatory molecules that enhance the body's immune response to cancer. Nanoparticle vaccines, which co-deliver antigens and adjuvants, are being developed to stimulate T-cell responses and promote tumor eradication (Ferrero-Miliani et al., 2007).Several nanotechnology-based cancer treatments have demonstrated promising results. For example, CRLX101, a nanoparticle-formulated chemotherapy drug, has shown improved targeting and effectiveness.

Additionally, nanoparticles delivering the molecule IPA-3 have exhibited potential in prostate cancer treatment in laboratory mice. Further advancements include nanoparticles designed to enhance chemotherapy drug retention in brain tumors and gold nanoparticles activated by infrared light to destroy breast cancer tumors. Nanoparticles with radioactive cores are also being investigated for lymphoma treatment, allowing radiation to be concentrated at tumor sites while minimizing damage to healthy tissue. Notably, bismuth nanoparticles have been shown to improve radiation therapy by concentrating radiation doses at tumors, leading to a 90% increase in treatment effectiveness (Thadkala et al., 2015).

Hypertension

Hypertension is traditionally managed using various antihypertensive medications, including angiotensin-converting enzyme (ACE) inhibitors, calcium channel blockers, angiotensin receptor antagonists, diuretics, and adrenergic blockers (Sharma et al., 2016). Common ACE inhibitors, such as enalapril, benazepril, ramipril, and captopril, function by inhibiting the conversion of angiotensin I to angiotensin II while preventing the breakdown of bradykinin (Rachmawati et al., 2016). However, these drugs often suffer from limitations such as low bioavailability, short half-life, and undesirable side effects. To address these challenges, nanotechnology-based drug delivery systems have been developed to enhance drug stability, selectivity, and bioavailability while reducing adverse effects and dosing frequency (Sharma et al., 2016).

One promising approach involves formulating curcumin, a bioactive compound with antioxidant and anti-inflammatory properties, into a nanoemulsion system to enhance its solubility and therapeutic potential for hypertension. Studies have shown that while curcumin in its natural form exhibits limited ACE inhibition, its nanoemulsion formulation significantly improves bioavailability and antihypertensive efficacy (Rachmawati et al., 2016).

Other nanotechnology-based strategies have also been explored to optimize antihypertensive drug delivery. For instance, solid lipid nanoparticles (SLNs) containing carvedilol have been proposed to enhance the bioavailability of this poorly soluble drug (Venishetty et al., 2012). Similarly, SLNs loaded with nitrendipine, an antihypertensive drug with low oral bioavailability, demonstrated a three- to four-fold increase in bioavailability compared to conventional formulations (Kumar et al., 2007). Additionally, dendrimer-based drug delivery systems incorporating candesartan cilexetil have been found to improve the drug's water solubility, further enhancing its therapeutic potential (Gautam and Verma, 2012).

Nanosuspension-based formulations have also shown promise in improving drug dissolution rates, absorption, and overall bioavailability. For example, oral tablets derived from a nanosuspension of nebivolol hydrochloride exhibited superior absorption compared to conventional formulations (Thadkala et al., 2015). Other nanotechnology-based drug delivery methods, including polymeric nanoparticles, carbon nanotubes, polymeric micelles, nanocrystals, and liposomes, are being explored to optimize antihypertensive therapies (Sharma et al., 2016).

Furthermore, nanoparticles loaded with telmisartan have been developed to enhance the drug's solubility and dissolution rate, leading to a tenfold increase in bioavailability (Bajaj et al., 2012). Advances in nitric oxide (NO) delivery systems have also introduced NO-releasing nanoparticles that provide sustained therapeutic concentrations, effectively reducing blood pressure. A chitosan-polyethylene glycol nanoparticle platform for NO delivery demonstrated a dose-dependent reduction in mean arterial pressure, highlighting its potential in hypertension treatment (Cabrales et al., 2010).

Inflammatory Bowel Diseases

Inflammatory bowel diseases (IBD), including Crohn's disease and ulcerative colitis, are commonly managed with anti-inflammatory drugs such as aminosalicylates, immunosuppressants, biological agents, and corticosteroids. However, these treatments often lead to adverse effects, including allergic reactions, diarrhea, nausea, lymphopenia, and pancreatitis, largely due to their systemic absorption (Beloqui et al., 2016). As a result, there is a growing interest in developing safer and more effective therapeutic strategies for managing IBD (Bribi et al., 2016; Castro et al., 2015; Wang et al., 2021).

Nanotechnology has emerged as a promising approach to enhance drug delivery for IBD treatment, improving the efficacy and specificity of therapeutic agents while minimizing systemic side effects. One notable strategy involves the use of nanoparticles designed to protect drugs from the harsh gastric environment and enable targeted release in the intestine. These nanoparticles are engineered to respond to high levels of reactive oxygen species (ROS), a characteristic feature of inflamed tissues in IBD. This ROS-responsiveness ensures selective drug delivery to affected sites, significantly reducing systemic absorption and associated side effects. Compared to traditional gastro-resistant formulations, this nanotechnology-based approach has demonstrated a tenfold reduction in drug permeability across the intestinal cell monolayer, thereby enhancing localized treatment efficacy while limiting unwanted adverse effects (Wang et al., 2021).

These advancements in nanotechnology highlight its potential to revolutionize IBD management by providing more precise, efficient, and safer therapeutic options. As research continues to refine these targeted drug delivery systems, they hold promise for significantly improving patient outcomes in the treatment of IBD.

7. CONCLUSIONS

Nanotechnology has transformed drug delivery systems, offering innovative solutions for the treatment of various inflammatory diseases, including cancer, hypertension, and inflammatory bowel disease (IBD). Traditional therapeutic approaches often face challenges such as poor bioavailability, systemic side effects, and inefficient targeting of diseased tissues. Nanotechnology-based drug delivery systems address these limitations by enhancing the solubility, stability, and bioavailability of therapeutic agents while ensuring precise delivery to affected sites.

In cancer therapy, nanoparticles enable targeted drug delivery, improve the retention of chemotherapeutic agents in tumors, and enhance the efficacy of radiation therapy, reducing damage to healthy tissues. Similarly, in hypertension management, nanocarrier-based formulations enhance the bioavailability and therapeutic potential of antihypertensive drugs, enabling sustained drug release and reducing adverse effects.

For IBD, nanotechnology facilitates targeted drug release in inflamed intestinal tissues, minimizing systemic absorption and improving treatment efficacy.

The primary goal of nanoformulations is to develop efficient, reliable drug delivery systems that optimize therapeutic outcomes while minimizing side effects. Advances in this field are expected to revolutionize treatment strategies by increasing drug concentration at the site of action, enhancing intracellular uptake, and ensuring controlled drug release. These innovations not only improve current treatment options but also lay the groundwork for future therapies that offer sustained disease management with reduced dosing frequency. As research continues to refine nanotechnology-based drug delivery systems, their application holds great promise for improving patient care and transforming the treatment of chronic inflammatory diseases.

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