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Nanotechnology in drug delivery systems and insights to advances in nanocarriers, liposomes, and micelles for targeted drug delivery and controlled release

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ABSTRACT

Nanotechnology has revolutionized the field of drug delivery, offering innovative solutions to longstanding challenges such as poor bioavailability, systemic toxicity, and non-specific distribution of therapeutic agents. This review highlights recent advances in nanocarrier systems particularly liposomes, micelles, and other engineered nanoparticles for targeted drug delivery and controlled release. A comprehensive literature review was conducted across leading scientific databases, including PubMed, ScienceDirect, Scopus, Web of Science, and Google Scholar, to explore recent advancements in nanotechnology-based drug delivery systems. The search utilized a combination of relevant keywords such as “nanotechnology,” “drug delivery systems,” “nanocarriers,” “liposomes,” “micelles,” “controlled release,” “targeted delivery,” “nanoformulations,” and “nanomedicine.” The review synthesized current developments in the design and application of nanocarriers—particularly liposomes, polymeric micelles, and other nanoformulations—that enhance drug solubility, stability, bioavailability, and site-specific delivery. Key strategies in controlled and sustained drug release were examined, along with the role of surface functionalization and stimuli-responsive mechanisms in achieving precise therapeutic targeting. Emphasis was placed on the integration of active targeting approaches, including ligand-mediated delivery systems, which have shown significant promise in oncology, infectious diseases, and neurological disorders. While nanotechnology has markedly advanced the field of drug delivery, several challenges persist, including issues related to biocompatibility, large-scale manufacturing, regulatory approval, and long-term safety. This review highlights the potential of nanomedicine to address the limitations of conventional drug delivery and improve clinical outcomes. Continued interdisciplinary research and strategic development are essential to overcome current barriers and facilitate the successful translation of nanocarrier technologies from the laboratory to clinical practice.

KEYWORDS: *Drug delivery systems, Nanocarriers, Liposomes, Micelles, Controlled release, Targeted drug delivery*

INTRODUCTION

Effective drug delivery remains one of the most critical challenges in modern medicine. Despite significant advances in pharmaceutical development, many therapeutic agents suffer from limitations such as poor bioavailability, rapid degradation or clearance, dose-limiting toxicity, and unintended interactions with healthy tissues [1]. These issues can reduce therapeutic efficacy, increase side effects, and hinder the treatment of complex diseases such as cancer, neurodegenerative disorders, and infectious diseases. Traditional drug delivery methods often fail to adequately address these challenges, necessitating innovative approaches to improve drug targeting, control release, and minimize systemic toxicity.

Nanotechnology has emerged as a transformative solution to these drug delivery challenges. By engineering materials at the nanoscale, researchers can develop drug carriers with enhanced properties such as improved solubility, prolonged circulation time, controlled release profiles, and the ability to target specific tissues or cells. Nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and inorganic nanomaterials can be functionalized with ligands for active targeting, allowing for precise delivery of therapeutic agents while sparing healthy tissues. This precision not only increases treatment efficacy but also reduces adverse effects, representing a paradigm shift in therapeutic strategies [2-4].

This review aims to provide a comprehensive overview of the current state of nanotechnology-enabled drug delivery systems, focusing on how these platforms address key limitations of conventional therapies. We will examine the various types of nanocarriers, their mechanisms of action, and recent advancements in their design and application. Additionally, the review will discuss the challenges and future prospects of translating nanotechnology-based drug delivery systems from bench to bedside. Through this discussion, we seek to highlight the potential of nanomedicine to revolutionize therapeutic delivery and improve patient outcomes across a broad spectrum of diseases [5].

Methods

This review was conducted using a systematic and integrative approach to collect, analyze, and synthesize relevant scientific literature on the applications of nanotechnology in drug delivery systems, with a specific focus on nanocarriers, liposomes, and micelles. The methodology followed ensures comprehensive coverage and critical evaluation of current advances in the field. A comprehensive literature search was performed across several major scientific databases, including **PubMed, ScienceDirect, Scopus, Web of Science, Google Scholar.** Keywords and search terms used included combinations of: *"nanotechnology", "drug delivery systems", "nanocarriers", "liposomes", "micelles", "controlled release", "targeted drug delivery", "nanoformulations", and "nanomedicine"*. Boolean operators (*AND*, *OR*) were used to refine the search and retrieve the most relevant articles. Filters were applied to focus on peer-reviewed articles published in English from **2010 to 2025**, prioritizing recent developments and breakthrough studies in the last five years.

Inclusion criteria

Peer-reviewed journal articles, reviews, and research papers were included in the study. Studies focusing on nanocarriers used in drug delivery, including liposomes, micelles, and polymeric nanoparticles alongside articles discussing controlled release, targeted delivery, or enhanced bioavailability were also considered. Publications highlighting clinical trials, in vitro/in vivo studies, or translational applications were similarly included.

Exclusion criteria

Non-English articles and studies unrelated to drug delivery or nanotechnology were excluded from this study. Articles without accessible full text, conference abstracts, editorials, or non-peer-reviewed materials were similarly excluded from this study.

Data extraction and analysis

After initial screening based on titles and abstracts, full texts of the eligible articles were reviewed. Key information was extracted and categorized under the following themes: Types of nanocarriers (e.g., liposomes, micelles, dendrimers, solid lipid nanoparticles) Mechanisms of drug delivery (passive vs. active targeting, stimuli-responsive release) Physicochemical properties (size, charge, surface modification) Therapeutic applications (oncology, infectious diseases, CNS disorders, etc.) Advantages and limitations Emerging trends and future perspectives A qualitative synthesis

was conducted, identifying patterns, common challenges, and novel innovations. Critical comparisons were made across nanocarrier platforms to highlight the most promising strategies for clinical translation.

Quality Assessment

To ensure reliability, only articles from high-impact journals or those frequently cited in the field were considered as core references. Where possible, the quality of included studies was assessed based on: Study design and reproducibility Clarity of methodology and experimental validation.

Results and Discussion

Fundamentals of nanotechnology in drug delivery

Nanotechnology involves the design, production, and application of materials and devices with dimensions typically ranging from 1 to 100 nanometers. At this scale, materials often exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. In the context of drug delivery, nanotechnology refers to the use of nanoscale systems such as nanoparticles, nanocapsules, nanoshells, and nanogels to encapsulate therapeutic agents and enhance their delivery to specific sites in the body. These nanocarriers can be engineered to improve the pharmacokinetics and pharmacodynamics of drugs, enabling more precise, efficient, and safer treatments [6].

Advantages of nanotechnology in pharmaceutical sciences

Nanotechnology offers several significant advantages in the field of drug delivery. One of the most prominent is the ability to enhance the solubility and stability of poorly water-soluble drugs, which are otherwise difficult to deliver effectively. Nanocarriers can also protect drugs from premature degradation in the biological environment, thus extending their circulation time and therapeutic window [7]. Moreover, due to their small size and surface modifiability, nanoparticles can cross biological barriers, such as the blood-brain barrier, that are typically impermeable to conventional drugs. Additionally, nanocarriers can be functionalized with targeting ligands (e.g., antibodies, peptides, or small molecules) that enable selective delivery to diseased tissues, thereby minimizing off-target effects and systemic toxicity [8].

Mechanisms of targeted and controlled drug release at the nanoscale

Nanotechnology enables both passive and active targeting strategies for drug delivery. Passive targeting exploits the enhanced permeability and retention (EPR) effect, a phenomenon observed in tumor and inflamed tissues where leaky vasculature allows nanoparticles to accumulate preferentially. Active targeting, on the other hand, involves the functionalization of nanocarriers with ligands that bind to specific receptors overexpressed on target cells, facilitating cellular uptake [9].

Controlled drug release is another critical feature of nanoscale drug delivery systems. Release profiles can be tailored by modifying the carrier composition, surface characteristics, and environmental responsiveness. Stimuli-responsive nanocarriers are particularly promising; they can release their payload in response to specific internal (e.g., pH, redox potential, enzymes) or external (e.g., temperature, light etc) [10].

Nanocarriers classification and mechanisms

Nanocarriers are nanoscale delivery systems designed to transport therapeutic agents to specific sites in the body, improving drug efficacy while minimizing side effects. These advanced drug delivery vehicles have become essential in modern medicine, particularly in cancer therapy, gene delivery, and diagnostics. They function by protecting the drug from degradation, enhancing absorption, and enabling targeted or controlled release [11].

Nanocarriers are broadly classified into several types based on their composition and structure. One of the most commonly used types is polymeric nanoparticles, which are composed of biodegradable polymers such as PLGA (poly(lactic-co-glycolic acid)), PEG (polyethylene glycol), or chitosan. These nanoparticles are valued for their controlled release properties, biocompatibility, and the ease with which they can be modified to suit different therapeutic needs.

Another important category is solid lipid nanoparticles (SLNs). These consist of a solid lipid core stabilized by surfactants. They combine the advantages of liposomes and polymeric nanoparticles, offering high drug stability and controlled release, and are well-suited for various routes of administration, including oral and topical [12].

Dendrimers represent a unique class of nanocarriers characterized by a highly branched, tree-like structure. Their architecture allows for a high degree of functionalization, enabling the attachment of multiple drugs, targeting ligands, or imaging agents. Their precise molecular size and shape make them especially useful for applications in gene therapy and diagnostic imaging.

Nanoemulsions, which are emulsified systems with nanometer-sized droplets, are also widely used. These can be oil-in-water or water-in-oil formulations and are particularly effective at delivering poorly water-soluble drugs. Their high surface area enhances absorption and bioavailability, making them ideal for oral, topical, and ocular drug delivery [13].

Lastly, inorganic nanoparticles, such as gold and silica nanoparticles, offer unique physical and chemical properties. These include optical and magnetic characteristics that make them suitable for theranostic applications simultaneously diagnosing and treating diseases. Gold nanoparticles, for example, can be used for photothermal therapy, while silica nanoparticles are often employed in imaging and biosensing [14].

The mechanisms by which nanocarriers deliver drugs can vary. Passive targeting takes advantage of the enhanced permeability and retention (EPR) effect, particularly in tumor tissues where leaky vasculature allows nanoparticles to accumulate. Active targeting involves modifying the nanocarrier surface with specific ligands, such as antibodies or peptides, which bind to receptors on target cells, enhancing specificity and uptake.

Additionally, nanocarriers can be engineered for controlled or stimuli-responsive release, where the drug is released in response to specific triggers such as changes in pH, temperature, or the presence of certain enzymes. This allows for spatial and temporal control over drug delivery. Once at the target site, nanocarriers often enter cells via endocytosis and can release their payloads intracellularly, sometimes reaching the cytoplasm or even the nucleus, depending on the application [15].

Mechanisms of drug loading and release

Drug delivery systems have evolved significantly over the past decades, with liposomes emerging as one of the most versatile and widely studied carriers. These spherical vesicles, composed of one or more phospholipid bilayers surrounding an aqueous core, offer a unique structure that allows for the encapsulation of both hydrophilic and lipophilic drugs. Hydrophilic drugs are typically housed in the aqueous core, while lipophilic compounds integrate into the lipid bilayer, making liposomes suitable for a wide range of therapeutic agents [17].

The release of drugs from liposomal systems can occur through several primary mechanisms. Diffusion is the most straightforward, where drug molecules gradually migrate out of the liposome due to a concentration gradient. This process is influenced by factors such as the drug's solubility, membrane permeability, and environmental conditions. Another mechanism is erosion, where the liposomal membrane or carrier matrix degrades over time, leading to the gradual release of the encapsulated drug. This is particularly useful for achieving sustained or controlled release profiles [17-19].

In recent years, stimuli-responsive release mechanisms have gained attention due to their potential for precise, site-specific drug delivery. These systems are designed to respond to specific physiological triggers such as changes in pH, temperature, or the presence of certain enzymes. For instance, pH-sensitive liposomes remain stable in the bloodstream but release their payload in acidic environments like tumor tissues or intracellular endosomes. Similarly, thermo-sensitive liposomes are engineered to release their contents when exposed to mild hyperthermia, a condition often induced during cancer treatment. Enzyme-responsive systems exploit overexpressed or disease-specific enzymes to initiate drug release, adding another layer of selectivity [20].

Liposome technology has progressed beyond conventional formulations to include a range of advanced delivery systems. Conventional liposomes, while effective at encapsulating drugs, are often rapidly recognized and cleared by the body's immune system, particularly by the mononuclear phagocyte system (MPS). This limits their circulation time and, by extension, their therapeutic efficacy.

To overcome these limitations, stealth liposomes were developed. These are typically modified with polyethylene glycol (PEG), a process known as PEGylation, which masks the liposome surface from immune detection. As a result, stealth liposomes exhibit significantly prolonged circulation times and enhanced bioavailability,

making them suitable for chronic conditions and cancer therapy. An example of this technology in clinical use is Doxil®, a PEGylated liposomal formulation of doxorubicin [21]. Further enhancements include ligand-targeted liposomes, which are functionalized with specific ligands such as antibodies, peptides, or aptamers. These ligands bind selectively to receptors overexpressed on target cells, such as cancerous cells, enabling targeted drug delivery and minimizing off-target effects. This active targeting approach holds great promise for personalized medicine and treatments requiring high specificity [22].

In addition, stimuli-sensitive liposomes represent a cutting-edge advancement in liposomal design. These smart systems respond to specific internal or external triggers such as acidic pH, elevated temperatures, or disease-specific enzymes thus ensuring that the drug is released precisely where and when it is needed. Such precision not only improves therapeutic outcomes but also reduces systemic toxicity and side effects.

Diffusion, erosion, stimuli-responsive triggers

Micelles have emerged as powerful vehicles for drug delivery, particularly due to their unique ability to encapsulate hydrophobic drugs within their core and deliver them in a controlled, targeted fashion. These nanoscale structures form through the self-assembly of amphiphilic molecules—compounds that possess both hydrophilic (water-attracting) and hydrophobic (water-repelling) regions—when placed in an aqueous environment. Above a certain concentration, known as the critical micelle concentration (CMC), these molecules spontaneously organize into micelles. The hydrophobic segments cluster inward to avoid water, creating a core, while the hydrophilic portions form an outer shell that interfaces with the surrounding aqueous medium [23].

There are two primary types of micelles commonly used in drug delivery: surfactant micelles and polymeric micelles. Surfactant micelles are formed from low-molecular-weight surfactants and tend to be small and relatively unstable in the bloodstream due to their higher CMC. This makes them prone to disassembly upon dilution, which can lead to premature drug release. In contrast, polymeric micelles are made from amphiphilic block copolymers and exhibit significantly greater stability due to their lower CMC values and stronger core–shell architecture. These structures are generally larger and more stable, making them more suitable for systemic drug delivery where prolonged circulation and controlled release are essential.

Micelles can also be functionally enhanced to improve their performance in vivo. One important advancement is the development of stimuli-responsive micelles, which are engineered to release their drug payload in response to specific physiological triggers. For example, pH-sensitive micelles can exploit the acidic environment of tumor tissues or intracellular compartments to initiate drug release. Other micelles may respond to temperature changes, redox conditions, or the presence of specific enzymes, each trigger enabling precise spatial and temporal control over drug delivery [24].

In addition to responsiveness, micelles can be modified to actively target specific cells or tissues. This is achieved by attaching targeting ligands to their surface, such as antibodies, peptides, aptamers, or small molecules. These ligands are chosen to recognize and bind to receptors that are overexpressed on the surface of diseased cells, such as tumor cells. Targeted micelles can significantly enhance the uptake of therapeutic agents by diseased cells through receptor-mediated endocytosis while minimizing off-target effects on healthy tissues [25].

The most significant application of micelles in drug delivery lies in their ability to carry hydrophobic drugs. Many potent chemotherapeutic agents suffer from poor water solubility, limiting their clinical effectiveness. Micelles can encapsulate these drugs within their hydrophobic cores, improving solubility, stability, and bioavailability. Furthermore, polymeric micelles, in particular, benefit from prolonged circulation times in the bloodstream. Their hydrophilic outer shells, often composed of poly(ethylene glycol) (PEG), help evade the immune system by reducing protein adsorption and clearance by phagocytic cells. This “stealth” behavior allows micelles to accumulate in tumors through the enhanced permeability and retention (EPR) effect, a phenomenon where the leaky vasculature of tumor tissues permits the passive accumulation of nanoparticles, while poor lymphatic drainage limits their removal [26].

By combining long circulation times, responsive release mechanisms, and targeted delivery

capabilities, micelles enhance therapeutic efficacy while minimizing systemic toxicity. Their versatility makes them an attractive platform for cancer therapy and other diseases that benefit from localized drug action. As research advances, micelle-based drug delivery systems are expected to play an increasingly important role in the development of next-generation therapeutics, offering safer and more efficient treatments for complex medical conditions [27].

Controlled drug release mechanisms

Controlled drug release mechanisms are a cornerstone of modern pharmaceutical science, offering precise regulation over when and where a therapeutic agent is released in the body. These systems are designed to optimize drug efficacy, reduce side effects, and improve patient compliance by tailoring the delivery profile to the needs of specific diseases or patient conditions. One major area of innovation in controlled drug delivery involves temporal and spatial control. Temporal control refers to how the drug is released over time. In sustained release systems, drugs are delivered gradually over an extended period, maintaining consistent therapeutic levels and minimizing dosing frequency [28]. Delayed release systems are engineered to hold off on drug release until a specific time or until the dosage form reaches a particular part of the body—for example, enteric-coated tablets that resist stomach acid and dissolve in the intestine. Another approach is pulsatile release, where the drug is discharged in bursts at predetermined intervals. This can be particularly beneficial for treating diseases with circadian patterns, such as asthma or rheumatoid arthritis [29]. Spatial control, on the other hand, focuses on delivering drugs to specific sites within the body. This precision targeting can be achieved through a variety of strategies, such as attaching ligands that bind to receptors on target cells, using magnetic fields to guide drug-laden particles, or employing external triggers like ultrasound or light to localize the release. Beyond time and location-based control, researchers have developed stimuli-responsive drug delivery systems, also known as "smart" systems. These mechanisms rely on either internal or external stimuli to trigger drug release. Internal stimuli-responsive systems take advantage of physiological differences in the body. For example, pH-responsive systems are designed to release drugs in environments with abnormal pH levels, such as the acidic microenvironment of tumors. Redox-responsive systems exploit the higher concentration of reducing agents like glutathione inside cells to initiate drug release. Other systems respond to enzymes that are overexpressed in diseased tissues [30].

External stimuli-responsive systems are activated by external forces. Temperature-sensitive carriers can release drugs when exposed to heat, often through localized hyperthermia. Magnetic field-responsive systems use magnetic nanoparticles that can be guided and heated by external magnets to trigger release. Similarly, light-activated systems, including those triggered by UV or near-infrared (NIR) light, enable precise control of drug release at targeted sites. Ultrasound can also be used, employing mechanical vibrations or localized heating to initiate release [31].

At the heart of many of these advanced strategies are smart nanocarriers with engineered nanoscale delivery systems that combine multiple functionalities. These include liposomes, dendrimers, polymeric micelles, mesoporous silica nanoparticles, and metal-organic frameworks. Smart nanocarriers can be designed to recognize and bind to specific cells, respond to environmental stimuli, and release their payloads in a controlled fashion. Their surfaces can be functionalized with ligands, antibodies, or peptides for active targeting, and they are typically engineered to be biocompatible and minimize immune system activation.

These sophisticated delivery systems are particularly promising for treating complex conditions such as cancer, inflammatory diseases, neurological disorders, and infections. By integrating temporal control, spatial targeting, and stimuli-responsiveness, controlled drug release systems—especially smart nanocarriers which represent a powerful and versatile approach in the field of precision medicine [32].

Clinical applications and translational progress

Nanomedicine has rapidly evolved from a conceptual field into a practical approach with significant clinical impact. Early research focused on preclinical studies where various nanocarriers such as liposomes, dendrimers, polymeric nanoparticles, and inorganic systems having demonstrated considerable promise. These nanoscale delivery systems offered notable improvements in drug solubility, protection from degradation, targeted delivery to specific tissues or cells, and controlled release over time. In

animal models, such platforms often resulted in enhanced therapeutic efficacy, reduced toxicity, and more favorable pharmacokinetics compared to conventional formulations.

Building upon these successes, numerous nanomedicine products have progressed into clinical trials. Human studies have explored their safety profiles, biodistribution, metabolism, and therapeutic benefits across a range of diseases. These trials typically evaluate endpoints such as tumor accumulation, treatment efficacy, and systemic side effects. The ongoing success of these trials continues to bridge the gap between laboratory innovation and real-world clinical application [33].

Several nanoformulations have already received FDA approval, signaling a key milestone in the translation of nanotechnology to mainstream medicine. One of the earliest and most well-known examples is Doxil®, a pegylated liposomal formulation of doxorubicin, approved for the treatment of ovarian cancer and Kaposi's sarcoma. Another widely used formulation is Abraxane®, an albumin-bound form of paclitaxel that eliminates the need for toxic solvents and is approved for breast, lung, and pancreatic cancers. In hematological malignancies, Vyxeos®, a liposomal formulation combining daunorubicin and cytarabine at a fixed molar ratio, has shown improved outcomes in certain types of leukemia. The approval of Onpattro®, a lipid nanoparticle formulation delivering small interfering RNA (siRNA), marked the first FDA-approved RNA interference therapy, representing a new class of gene-silencing treatments. More recently, lipid nanoparticle platforms have also played a critical role in the rapid development and deployment of mRNA-based COVID-19 vaccines, such as those by Pfizer-BioNTech and Moderna.

Nanomedicine has found significant applications in several major disease areas. In oncology, nanocarriers are particularly valuable due to their ability to exploit the enhanced permeability and retention (EPR) effect, leading to preferential accumulation in tumor tissues. Liposomal and polymeric systems allow for more targeted chemotherapy with reduced systemic toxicity. Additionally, nanoparticles are increasingly being engineered for combination therapies, imaging-guided treatment, and immunotherapy enhancement [34, 35].

In the field of infectious diseases, nanoformulations like liposomal amphotericin B have improved safety profiles, notably reducing the nephrotoxicity associated with antifungal treatment. Nanocarriers are also being investigated for targeted antibiotic delivery and as vaccine adjuvants to improve immune responses. The success of lipid nanoparticle-based mRNA vaccines has further highlighted the value of nanotechnology in infectious disease prevention and management.

Central nervous system (CNS) disorders represent another frontier where nanomedicine shows great potential. One of the major challenges in treating CNS conditions is the presence of the blood-brain barrier (BBB), which restricts the entry of most drugs into the brain. Nanoparticles are being designed to cross this barrier via receptor-mediated transport mechanisms, enabling the delivery of therapeutic agents for diseases such as Alzheimer's, Parkinson's, and glioblastoma. Preclinical studies in this area are promising, with various platforms showing the ability to deliver neuroprotective agents, anti-inflammatory drugs, and even gene therapies directly to brain tissue [36].

In summary, nanomedicine has made impressive strides in clinical translation. With multiple FDA-approved products and many more in development, it is reshaping how we approach the diagnosis, treatment, and prevention of complex diseases. As new materials, targeting strategies, and regulatory frameworks continue to evolve, nanotechnology is poised to play an even greater role in the future of personalized and precision medicine.

Challenges and future perspectives

Nanomedicine, while offering transformative potential for diagnostics and therapeutics, faces several key challenges that must be addressed to fully realize its promise. One of the primary concerns is stability and scalability. Many nanomaterials exhibit instability under physiological conditions, which can compromise their therapeutic efficacy and safety. Furthermore, scaling up the production of these materials while maintaining consistency (i.e., size, shape, and functionality), remains a complex and costly endeavor [37]. These issues hinder the transition from laboratory research to large-scale clinical application.

Another significant challenge lies in toxicity and immunogenicity. Although nanomaterials can be engineered for biocompatibility, unintended toxic effects and adverse immune responses are still

common. The interaction of nanoparticles with biological systems is highly complex and not yet fully understood, making it difficult to predict long-term effects. Comprehensive and standardized toxicity studies are needed to ensure that nanomedicines do not pose risks to patients.

Regulatory and manufacturing challenges further complicate the development of nanomedicines. Regulatory frameworks have yet to catch up with the unique properties and mechanisms of action associated with nanoscale therapeutics. There is a lack of standardized protocols for characterization, testing, and quality control, which delays approval processes and increases the burden on developers. Additionally, manufacturing nanomedicines with reproducibility and in compliance with good manufacturing practices (GMP) is technically demanding and often expensive [38].

Looking ahead, the field of nanomedicine is expected to evolve in exciting new directions. Personalized nanomedicine is a particularly promising trend, aiming to tailor nanoparticle-based therapies to individual patients based on their genetic, biochemical, and environmental profiles. This approach could significantly improve treatment efficacy and reduce side effects. Another emerging area is the development of hybrid systems, which combine different types of nanomaterials or integrate nanotechnology with other therapeutic modalities, such as gene editing or immunotherapy. These systems can offer multifunctionality, enhanced targeting capabilities, and synergistic therapeutic effects.

Looking ahead, nanotechnology is poised to play a transformative role in the next generation of therapeutic strategies. Advances in precision engineering, biomimicry, and smart nanomaterials will continue to enhance the safety and efficacy of nanodrugs. However, challenges such as large-scale manufacturing, long-term toxicity studies, and regulatory approval must be addressed to fully realize the clinical potential of these systems. As interdisciplinary collaborations grow and regulatory pathways mature, nanotechnology is expected to become an integral part of mainstream medical treatments.

In summary, while nanomedicine holds enormous potential, overcoming current challenges related to stability, safety, regulation, and production is essential. Continued interdisciplinary research, innovation in nanomaterial design, and the development of adaptive regulatory frameworks will be critical in shaping the future of this rapidly evolving field.

Conclusion

Recent developments in nanotechnology have revolutionized the field of drug delivery, offering targeted, efficient, and controlled therapeutic options. Key advances include the creation of stimuli-responsive nanocarriers, surface-functionalized nanoparticles for specific cell targeting, and multifunctional platforms that combine diagnostics with therapeutics (theranostics). Innovations in lipid-based, polymeric, and inorganic nanocarriers have also improved the solubility, bioavailability, and stability of drugs, while reducing systemic toxicity. The integration of nanotechnology in modern medicine holds the potential to overcome many of the limitations of traditional drug delivery systems. Personalized nanomedicine approaches can optimize treatment outcomes for various diseases, especially cancer, neurological disorders, and infectious diseases. Furthermore, nanocarriers can traverse biological barriers, such as the blood-brain barrier, and enable site-specific drug delivery, reducing side effects and improving patient compliance.

Ethical Considerations

Data availability

The data that supported the findings in this study are available on request from the corresponding author

Conflict of interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest.

Compliance with ethical guidelines

Approval for this study and related cases was obtained from the University of Uyo Health Research Ethics Committee

Author's contribution

The authors confirm contributions as follows: study conception and design by SOA; data collection by PJE, GO and AEA; Analysis and interpretation of results by all authors; Draft manuscript preparation by SOA; all authors reviewed the result and approved the final version of the manuscript.

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