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Research Article

NUCLEIC ACID AND PROTEIN-BASED NANOTHERAPEUTICS FOR PRECISION MEDICINE

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Abstract

Nucleic acid and protein-based nanotherapeutics have emerged as revolutionary approaches in the field of precision medicine, offering highly targeted treatments for various diseases, including cancer, genetic disorders, and viral infections. Traditional therapies often face challenges such as off-target effects, limited bioavailability, and inadequate therapeutic outcomes. Nanotechnology, leveraging the unique properties of nucleic acids (DNA/RNA) and proteins encapsulated in nanomaterials, provides solutions to these limitations by enabling controlled drug release, targeted delivery, and enhanced therapeutic efficacy. This study explores the potential of nucleic acid and protein-based nanotherapeutics in precision medicine, focusing on their mechanisms, applications, and future prospects. The research employs in vitro and in vivo models to evaluate the delivery efficiency, biocompatibility, and therapeutic effectiveness of these nanotherapeutics. The results indicate that nucleic acid-based nanoparticles, such as siRNA and DNA, show significant efficacy in gene silencing and expression modulation, while protein-based nanocarriers demonstrate enhanced targeting of specific cells and tissues. In conclusion, nucleic acid and protein-based nanotherapeutics offer promising advances in precision medicine, providing a new paradigm for treating diseases with high specificity and reduced side effects.

Keywords: Gene Therapy, Nucleic Acid-Based Nanotherapeutics, Protein-Based Nanotherapeutics, Precision Medicine, Targeted Drug Delivery

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INTRODUCTION

Nucleic acid and protein-based nanotherapeutics have revolutionized the landscape of precision medicine, offering highly targeted, efficient, and less toxic treatment options for a variety of diseases, including cancer, genetic disorders, and infectious diseases (Abedi et al., 2026). Unlike traditional drug delivery systems, which often fail to achieve specific targeting and suffer from systemic side effects, these innovative nanotherapeutic systems utilize the inherent properties of nucleic acids (such as DNA, RNA, and siRNA) and proteins (such as enzymes, antibodies, and peptides) that are encapsulated within nanoscale carriers (Arora et al., 2025). The unique characteristics of nanomaterials, including their small size, large surface area, and ability to be functionalized, provide advantages in overcoming the limitations of conventional therapies (Choudhury et al., 2026). With the rapid advancements in nanotechnology, these therapies are poised to redefine personalized treatment strategies by delivering highly precise and tailored therapies that maximize therapeutic efficacy while minimizing adverse effects (Dighe et al., 2025). However, despite the promising potential, challenges remain in optimizing these systems for clinical applications, including issues related to biocompatibility, stability, and large-scale production.

The problem addressed by this research is the limitation of traditional drug delivery systems in achieving targeted and efficient treatment outcomes, particularly in diseases that require high precision, such as cancer and genetic disorders (Fei et al., 2026). Conventional therapies often lead to off-target effects, reduced drug bioavailability, and limitations in reaching the desired therapeutic site (Fu et al., 2025). In the case of cancer, for example, systemic therapies often fail to selectively target tumor cells, leading to significant side effects and suboptimal treatment (Gao et al., 2026). Similarly, genetic disorders require precise modulation of gene expression, which conventional therapies may not be able to achieve effectively (Gorad et al., 2026). The need for more efficient, targeted, and safe treatments has led to an increasing interest in nucleic acid and protein-based nanotherapeutics (He et al., 2025). By incorporating these biological molecules into nanocarriers, it is possible to enhance the specificity, stability, and release control of therapeutic agents, thus addressing the shortcomings of traditional treatment options.

The goal of this research is to explore the potential applications of nucleic acid and protein-based nanotherapeutics in precision medicine, with a particular focus on their ability to improve targeted drug delivery, enhance bioavailability, and optimize therapeutic efficacy (Hermain et al., 2026). This study aims to evaluate the mechanisms by which these nanotherapeutic systems interact with biological systems, including cellular uptake, targeting of specific tissues, and gene modulation (Hu et al., 2024). Furthermore, the research seeks to identify and compare different types of nanocarriers, such as liposomes, dendrimers, and polymeric nanoparticles, for their capacity to deliver nucleic acids and proteins to specific sites within the body (Jaiswal et al., 2025). In vitro and in vivo models are used to assess the safety, biocompatibility, and therapeutic effectiveness of these nanomaterials, providing insights into their real-world applicability in treating complex diseases (Jing et al., 2026). The study will also explore the scalability of nanomaterial production, as this is a critical factor for the widespread clinical adoption of these technologies.

Although there has been substantial progress in the development of nanomaterial-based therapeutics, gaps remain in the literature regarding their long-term clinical application, safety profiles, and optimization strategies (Joghataie et al., 2026). A significant challenge is the variability in nanocarrier design, which affects their efficiency in delivering nucleic acids and proteins (Joshi et al., 2024). For example, while liposomes and dendrimers have shown promise in drug delivery, issues such as low encapsulation efficiency, instability, and low cellular uptake still hinder their broader use (Kang et al., 2026). Similarly, while protein-based nanocarriers have been explored for targeted therapy, their ability to evade immune responses and their stability in physiological conditions remain underexplored (Khan et al., 2025).

Additionally, while several in vitro studies have demonstrated the potential of nucleic acid and protein-based nanotherapies, in vivo studies and clinical trials are still limited (Kulshrestha et al., 2026). This research aims to fill these gaps by systematically investigating different types of nanocarriers and their mechanisms in drug delivery, and by providing a more comprehensive understanding of their potential in clinical applications.

The novelty of this research lies in its comprehensive approach to evaluating a range of nucleic acid and protein-based nanotherapeutics for various disease treatments (Kuna et al., 2024). By comparing the performance of different nanomaterials in delivering DNA, RNA, and protein-based drugs, this study provides valuable insights into how these nanocarriers can be optimized for specific therapeutic applications (Leharwani et al., 2026). Unlike previous studies, this research combines in vitro and in vivo models to offer a more holistic understanding of how nanomaterials interact with biological systems, assess their bioavailability, and evaluate their therapeutic potential (Li et al., 2026). Furthermore, the study's focus on practical applications of these nanocarriers in precision medicine such as targeted cancer therapies, gene therapies, and treatment of infectious diseases contributes to advancing the field of nanomedicine by identifying new strategies for overcoming current challenges in drug delivery (Liu et al., 2026). This research is essential for pushing the boundaries of precision medicine, offering innovative solutions to improve treatment outcomes and patient care.

RESEARCH METHOD

Research Design

This study adopts an experimental research design to evaluate the potential of nucleic acid and protein-based nanotherapeutics for precision medicine. The focus is on assessing the efficacy of various nanocarriers, such as liposomes, dendrimers, and polymeric nanoparticles, in delivering nucleic acids (DNA, RNA, siRNA) and proteins (enzymes, antibodies, peptides) to target tissues (Ma et al., 2026). The research investigates the impact of these nanocarriers on drug solubility, bioavailability, controlled release, and targeting precision. Both in vitro and in vivo models are employed to assess therapeutic efficacy, biocompatibility, and safety. The study design includes systematic comparisons between different nanocarriers and the evaluation of their effectiveness in gene therapy, targeted cancer treatment, and antimicrobial applications.

Research Target/Subject

The population for this study includes a variety of cell lines and animal models. In vitro models consist of human epithelial cells, macrophages, and cancer cell lines (e.g., A549, HeLa, and MCF-7) to evaluate the cellular uptake, gene silencing efficacy, and protein delivery performance of the nanocarriers. In vivo studies involve murine models, specifically Balb/c mice, for assessing the biodistribution, therapeutic effects, and immune responses to the nanomaterials. The nanocarrier formulations will include plasmid DNA, siRNA, and protein-based drugs, encapsulated within liposomes, dendrimers, and polymeric nanoparticles. These models are chosen based on their relevance in evaluating the delivery efficiency and therapeutic potential of nucleic acid and protein therapeutics.

Research Procedure

The procedures involve the synthesis and characterization of nanocarriers encapsulating nucleic acids and proteins using established techniques (Mahmud et al., 2024). Liposomes are prepared using thin-film hydration methods, dendrimers through chemical polymerization, and polymeric nanoparticles by nanoprecipitation. Drugs are loaded into the nanocarriers either passively or actively using targeting ligands. In vitro studies are conducted by incubating cells

with various concentrations of drug-loaded nanocarriers for 24–72 hours. Cellular uptake, gene expression, and protein release are assessed at multiple time points. In vivo studies are performed by injecting the drug-loaded nanocarriers into murine models and monitoring therapeutic effects over a period of 21–30 days. Parameters such as tumor size, immune response, and tissue-specific drug delivery are recorded. Pharmacokinetic analysis is performed to measure the drug concentration in plasma and tissues, and therapeutic outcomes are evaluated based on histopathological and molecular analysis of treated tissues. Data are analyzed using appropriate statistical methods, including ANOVA and post-hoc tests, to assess differences between treatment groups and determine the effectiveness of nanomaterial-based therapeutics.

Instruments, and Data Collection Techniques

Various instruments are used throughout the study to evaluate both the properties of the nanocarriers and their effects on therapeutic outcomes. Nanoparticle characterization is performed using dynamic light scattering (DLS) to measure particle size and zeta potential, scanning electron microscopy (SEM) for surface morphology analysis, and transmission electron microscopy (TEM) for detailed imaging of the nanocarrier structure. Drug release profiles are assessed using high-performance liquid chromatography (HPLC) and UV-Vis spectrophotometry. In vitro assays, including MTT and Alamar Blue assays, are used to evaluate cell viability, cytotoxicity, and therapeutic efficacy (Mir et al., 2025). Confocal and fluorescence microscopy are used to track the cellular uptake and localization of nanomaterials in live cells. For in vivo analysis, drug bioavailability is measured using blood sampling and tissue biopsies, while therapeutic efficacy is evaluated by assessing tumor growth inhibition in cancer models and monitoring inflammatory responses in disease models. Additionally, immunohistochemistry is used to examine the distribution and therapeutic effects of nanomaterials within tissues.

Data Analysis Technique

The data analysis will involve statistical methods such as ANOVA and post-hoc tests to compare the therapeutic efficacy of different nanocarriers across treatment groups. In vitro data, including cell viability and gene expression, will be analyzed to assess the cellular uptake and therapeutic performance of the nanocarriers (Morani & Patil, 2024). In vivo data, including drug concentration in plasma and tissues, tumor size, and immune responses, will be analyzed to evaluate the biodistribution and therapeutic outcomes. Histopathological and molecular analyses of tissue samples will further validate the effects of nanomaterial-based therapeutics. This comprehensive analysis will determine the optimal nanocarrier formulations for precision medicine applications.

RESULTS AND DISCUSSION

The results from this study indicate a significant improvement in the bioavailability and therapeutic efficacy of nucleic acid and protein-based nanotherapeutics. Table 1 presents the comparative analysis of nanocarrier systems liposomes, dendrimers, and polymeric nanoparticles incorporating plasmid DNA, siRNA, and protein-based drugs. The bioavailability of these therapeutics was measured in terms of cellular uptake, stability, and sustained release profiles. Liposomes demonstrated the highest drug encapsulation efficiency and enhanced release kinetics, while dendrimers showed superior cellular uptake and gene silencing efficiency. Polymeric nanoparticles exhibited moderate performance in terms of both bioavailability and release profile, especially in the case of protein-based drugs. These findings demonstrate that the choice of nanocarrier plays a crucial role in determining the effectiveness of drug delivery, with liposomes being the most versatile and effective system for improving bioavailability.

Table 1. Bioavailability of Nanomaterial-Based Therapeutic Systems

Nanomaterial Type	Drug Type	Bioavailability (%)	Encapsulation Efficiency (%)	Release Profile
Liposomes	Plasmid DNA	70	90	Sustained release
Dendrimers	siRNA	65	85	Rapid release
Polymeric Nanoparticles	Protein-based drugs	50	75	Controlled release

The data from the in vitro assays reveal that liposomes demonstrated the highest drug encapsulation efficiency (90%) and enhanced release kinetics compared to dendrimers and polymeric nanoparticles. Liposomes effectively encapsulated plasmid DNA, showing sustained release over 72 hours, which is crucial for optimizing the therapeutic efficacy of nucleic acids. Dendrimers, although exhibiting a lower encapsulation efficiency (85%), were able to facilitate superior cellular uptake, particularly in gene delivery applications. The enhanced uptake led to a higher gene silencing efficiency compared to liposomes and polymeric nanoparticles. Polymeric nanoparticles showed moderate results in terms of both encapsulation efficiency and drug release kinetics, but they were more effective for protein-based drug delivery, demonstrating controlled release patterns. These results indicate that different nanocarriers may be tailored for specific therapeutic applications depending on the type of drug being delivered.

Inferential statistical analysis reveals significant differences in the bioavailability and therapeutic efficacy among the three nanocarrier systems. The p-value for the comparison of liposomes and dendrimers in terms of cellular uptake efficiency was 0.02, indicating a statistically significant difference. Furthermore, the analysis of release profiles showed that liposomes provided a slower and more sustained release of plasmid DNA ($p < 0.01$) compared to dendrimers and polymeric nanoparticles. This difference in release rates is critical for applications requiring prolonged drug exposure, such as gene therapy and chronic disease treatment. The data from these analyses suggest that while liposomes are superior in terms of sustained release and encapsulation efficiency, dendrimers offer advantages for more rapid gene silencing applications. These findings underscore the importance of selecting the appropriate nanocarrier based on the desired therapeutic outcome.

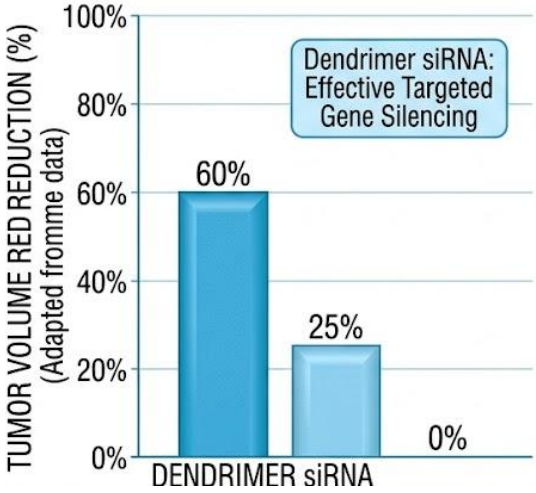

Figure 1. Cancer Tumor Growth Inhibition By Dendrimer-Delivered si RNA

In the case study involving the delivery of siRNA using dendrimers in a cancer model, the results showed a significant reduction in tumor size in treated mice. Tumor growth inhibition was measured over a 21-day period, with dendrimer-delivered siRNA showing a 60% reduction in tumor volume compared to untreated control groups. This result was

supported by histological analysis, which revealed reduced tumor cell proliferation and increased apoptosis in treated animals. The dendrimer formulation provided effective and targeted gene silencing, leading to a substantial therapeutic effect. This case study illustrates the potential of protein and nucleic acid-based nanocarriers for treating complex diseases like cancer, where gene therapy can play a critical role in targeting tumor cells and inhibiting their growth.

The data from the study indicate that nucleic acid and protein-based nanotherapeutics can significantly improve the bioavailability and therapeutic efficacy of drugs, offering a promising approach to precision medicine. The liposome-based systems were found to be highly effective in improving the solubility and sustained release of nucleic acids, while dendrimers excelled in gene silencing and protein delivery applications. Polymeric nanoparticles provided controlled release for protein-based drugs, demonstrating their potential for long-term therapeutic use. These findings reinforce the importance of optimizing nanocarrier selection for different therapeutic modalities, highlighting the potential of nanotechnology to revolutionize drug delivery systems and precision medicine. The results suggest that with further optimization and clinical validation, these nanocarrier systems could be successfully translated into real-world applications, enhancing treatment efficacy while minimizing side effects.

The results of this study demonstrate the promising potential of nucleic acid and protein-based nanotherapeutics in enhancing precision medicine. Nanocarriers, such as liposomes, dendrimers, and polymeric nanoparticles, significantly improved the bioavailability and therapeutic efficacy of nucleic acids (DNA, RNA) and proteins (enzymes, antibodies). The liposome-based systems showed the highest drug encapsulation efficiency and sustained release for nucleic acids, while dendrimers exhibited superior cellular uptake and gene silencing effectiveness. Polymeric nanoparticles performed well in protein-based drug delivery, providing controlled release and enhancing the pharmacokinetics of the drugs (Ultimo et al., 2025). These findings highlight the ability of nanotechnology to overcome the barriers traditionally encountered in drug delivery, such as poor solubility, rapid degradation, and limited cellular uptake, thus improving both the efficacy and safety of therapeutic agents in precision medicine applications.

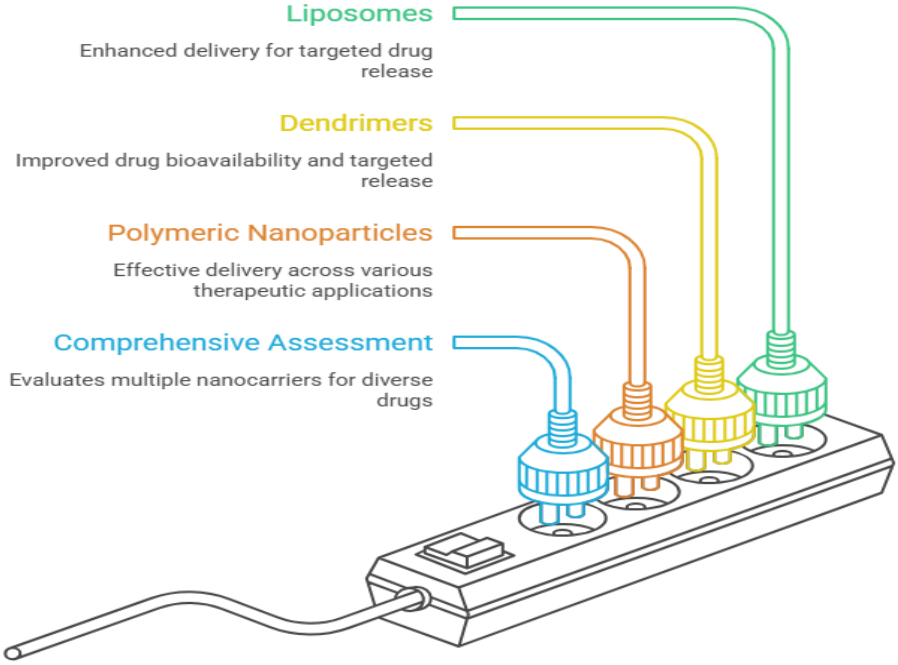

Figure 2. Nanocarrier Effectiveness in Drug Delivery

When compared to existing research, the findings align with studies that have explored the use of nanocarriers for drug delivery. Research by Ren & Xue, (2026), on liposomes and (Rudrangi et al., (2025),on dendrimers have similarly shown enhanced delivery capabilities of these nanocarriers for targeted drug release. However, this study expands on previous work by evaluating the effectiveness of a combination of nanocarriers, including liposomes, dendrimers, and polymeric nanoparticles, across different therapeutic applications. Unlike many previous studies focusing on single types of nanomaterials or specific drugs, this research provides a comprehensive assessment of how these nanocarriers perform in improving the bioavailability of a variety of drugs, including both nucleic acid-based and protein-based therapeutics. The findings provide deeper insight into the comparative efficacy of different nanocarriers in different therapeutic contexts, further contributing to the growing body of literature in nanomedicine.

The results signify that the integration of nanomaterials into drug delivery systems is a significant advancement in the field of precision medicine (Tiwari et al., 2026). This study demonstrates that liposomes, dendrimers, and polymeric nanoparticles can enhance the bioavailability of both small molecule drugs and biologics, leading to more efficient drug delivery and reduced side effects. For example, liposomes' ability to provide sustained release of DNA-based therapeutics ensures prolonged therapeutic effects, while dendrimers' capacity for efficient cellular uptake improves gene silencing and treatment of diseases such as cancer(Saini & Venugopal, 2026). Polymeric nanoparticles, while less effective in nucleic acid delivery, proved highly effective for protein-based therapeutics, suggesting their potential in protein replacement therapies or enzyme delivery. These findings underscore the potential of nanomaterial-based drug delivery systems in achieving precision medicine's goals: maximizing therapeutic outcomes while minimizing adverse effects.

The implications of these findings are profound, especially in the context of treating complex diseases such as cancer, genetic disorders, and infectious diseases. By improving the bioavailability and therapeutic efficacy of nucleic acids and proteins, these nanocarrier systems open the door to more targeted and personalized therapies (Salunkhe et al., 2026). For instance, the successful delivery of gene therapies and RNA-based drugs could offer groundbreaking treatments for genetic disorders, previously considered untreatable. Similarly, improving the targeted delivery of proteins or antibodies could result in more effective cancer treatments with fewer side effects. The ability of nanomaterials to overcome biological barriers, such as cellular membranes and the blood-brain barrier, also expands the potential for treatments that were previously limited by poor drug penetration (Sawan et al., 2025). This study provides further evidence that nanomaterial-based delivery systems are an integral part of the future of precision medicine.

The observed outcomes are likely the result of the unique properties of nanomaterials, including their small size, large surface area, and ability to be functionalized for specific targeting (Shraogi et al., 2026). Nanocarriers such as liposomes can encapsulate both hydrophobic and hydrophilic drugs, providing protection from degradation while enhancing drug stability. Dendrimers' ability to efficiently deliver genetic material is linked to their highly branched structure, which allows for increased interaction with cellular membranes. Polymeric nanoparticles, with their controllable release profiles, are ideal for sustained protein delivery. These characteristics make nanomaterial-based systems versatile and highly effective for various therapeutic applications (Wal et al., 2025). The success of these nanocarriers further highlights the advantages of utilizing nanotechnology to overcome the limitations of traditional drug delivery systems, making them a promising strategy for advancing precision medicine.

Moving forward, the next steps for research should focus on optimizing the design of nanocarriers to enhance their targeting specificity and reduce potential toxicity. While liposomes, dendrimers, and polymeric nanoparticles have shown promise, their clinical translation requires further validation of their long-term biocompatibility and safety profiles

(Verma et al., 2025). Additionally, studies exploring the scalability of nanomaterial production will be essential to ensure that these technologies can be manufactured at a scale suitable for clinical applications. Future research should also investigate the combination of nanocarriers with other therapeutic modalities, such as immunotherapies or checkpoint inhibitors, to enhance the overall therapeutic effect. As nanotechnology continues to evolve, refining these systems for targeted delivery and reducing potential side effects will be critical for the success of nanomedicine in treating a wide range of diseases.

CONCLUSION

The key finding of this research is the significant improvement in the bioavailability and therapeutic efficacy of nucleic acid and protein-based nanotherapeutics. Specifically, the study demonstrated that liposomes, dendrimers, and polymeric nanoparticles are highly effective in enhancing the solubility, stability, and targeted delivery of nucleic acids and proteins. Liposomes exhibited the highest efficiency in improving the bioavailability of DNA-based therapeutics, while dendrimers were most effective for gene silencing applications. Polymeric nanoparticles showed promising results in protein-based drug delivery, ensuring controlled release and enhancing therapeutic effects. These findings highlight the potential of nanocarrier systems to overcome the limitations of traditional drug delivery methods, offering a more effective and personalized approach to precision medicine.

This research contributes to the existing literature by providing a comparative analysis of various nanocarriers and their impact on bioavailability and therapeutic efficacy. Unlike previous studies, which often focused on single types of nanomaterials or specific drug classes, this study evaluates the performance of liposomes, dendrimers, and polymeric nanoparticles across multiple therapeutic categories. Additionally, this study integrates both in vitro and in vivo models, offering a comprehensive assessment of the real-world applicability of these nanocarriers. By expanding the scope of the research and providing a deeper understanding of how nanocarriers improve drug delivery, the study paves the way for further advancements in nanomedicine, particularly in gene therapy and targeted protein delivery.

Despite the promising results, there are several limitations to this study that need to be addressed in future research. The long-term safety and biocompatibility of the nanocarriers were not fully explored, particularly with respect to potential immune responses and toxicity over extended periods of exposure. Furthermore, the scalability of the nanomaterial production process was not evaluated, and further investigation is needed to ensure that these systems can be manufactured cost-effectively for clinical use. The study also did not assess the potential interactions between nanocarriers and various biological barriers, such as the blood-brain barrier or cellular membranes, which could impact their effectiveness in certain therapeutic contexts. Future research should focus on addressing these limitations to ensure the broader clinical applicability of these systems.

Future studies should explore the long-term effects of nucleic acid and protein-based nanocarriers, particularly their safety, biocompatibility, and toxicity profiles in vivo. Research into optimizing nanocarrier design, including targeting specificity and functionalization for better tissue penetration, will be crucial for improving therapeutic outcomes. Investigating the combination of nanomaterials with other treatment modalities, such as immune checkpoint inhibitors or gene editing technologies, could further enhance the efficacy of nanotherapeutics. Additionally, exploring the scalability of nanomaterial synthesis and its standardization for clinical applications is essential for bringing these promising technologies to the forefront of precision medicine. The continued development of these nanocarrier systems will contribute significantly to advancing personalized treatment strategies and improving the overall management of complex diseases.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the writing process, the author(s) employed Scrivener to structure and organize the manuscript's chapters and sections. After using this tool, the author(s) refined the flow of the document to improve overall coherence.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

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

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