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Research Article

BIODEGRADABLE NANOMATERIALS FOR TISSUE ENGINEERING AND REGENERATIVE MEDICINE APPLICATIONS

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Abstract

The field of tissue engineering and regenerative medicine has seen significant advancements with the use of nanomaterials, particularly biodegradable nanomaterials, which offer promising solutions for tissue regeneration and repair. These materials, due to their biocompatibility, biodegradability, and ability to mimic the extracellular matrix, play a crucial role in supporting cell growth, tissue development, and healing processes. Despite these promising properties, challenges remain regarding the optimization of nanomaterial performance, including controlled degradation rates and tissue-specific responses. This study aims to explore the potential of biodegradable nanomaterials in tissue engineering and regenerative medicine, focusing on their applications, properties, and functional enhancements through design optimization. The research aims to evaluate the efficacy of these nanomaterials in promoting tissue regeneration in various models, including bone, cartilage, and soft tissues. The study involves the synthesis and characterization of biodegradable nanomaterials, including nanofibers, nanoparticles, and hydrogels. In vitro cell culture assays and in vivo animal models are used to assess cell viability, proliferation, differentiation, and tissue regeneration potential. The study demonstrates that biodegradable nanomaterials significantly promote cell proliferation and differentiation, accelerating tissue repair and regeneration in all tested models. Controlled degradation rates of the nanomaterials contributed to sustained cell support and tissue integration. Biodegradable nanomaterials hold substantial promise for advancing tissue engineering and regenerative medicine, offering effective and sustainable solutions for tissue repair and regeneration.

Keywords: Biodegradable Nanomaterials, Cell Proliferation, Regenerative Medicine, Tissue Engineering, Tissue Regeneration

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INTRODUCTION

Tissue engineering and regenerative medicine have emerged as transformative fields in medical science, offering novel solutions for the repair and regeneration of damaged tissues. The development of biomaterials plays a pivotal role in these advancements, with biodegradable nanomaterials increasingly being recognized for their potential to address a variety of clinical challenges (Alex et al., 2024). Nanomaterials possess unique properties, such as high surface area, controllable degradation rates, and the ability to mimic the extracellular matrix, making them ideal candidates for use in tissue regeneration (Das & Parhi, 2025). Specifically, biodegradable nanomaterials, which break down safely within the body, are being explored for their ability to support cell growth, promote tissue integration, and enhance the repair process without the need for surgical removal (Amani et al., 2025). Their biocompatibility and degradation profiles offer a significant advantage over traditional materials, which may remain in the body and cause complications. This research explores the application of biodegradable nanomaterials for various tissue engineering strategies, including bone, cartilage, and soft tissue repair, highlighting their crucial role in the future of regenerative medicine.

The increasing demand for tissue replacements due to the rise of chronic diseases, injuries, and aging populations underscores the need for innovative materials capable of addressing these challenges (Azizollahi et al., 2026). Conventional treatments often fail to provide long-term solutions or result in complications due to foreign material rejection or mechanical failure over time. Nanomaterials, particularly those engineered to degrade at a controlled rate, are increasingly being utilized to meet these demands. The potential of biodegradable nanomaterials lies not only in their ability to replace damaged tissue but also in their capacity to integrate with natural tissue, stimulating regeneration and reducing the need for invasive surgical interventions (Bai et al., 2025). By offering an alternative to synthetic materials that may not integrate well with biological tissues, biodegradable nanomaterials represent a promising frontier in personalized medicine, offering solutions that are tailored to individual patient needs.

Recent studies have demonstrated the success of nanomaterials in drug delivery, tissue scaffolding, and gene therapy, emphasizing their versatility in therapeutic applications (Bal et al., 2026). However, the integration of nanomaterials into clinical settings, particularly in tissue engineering, remains fraught with challenges related to the biocompatibility, biodegradability, and effectiveness of these materials. While progress has been made in understanding how biodegradable nanomaterials interact with cells and tissues, significant gaps remain in optimizing these interactions for specific therapeutic needs (Bhattacharyya & Bal, 2026). The continued development of these materials is critical for the successful application of tissue engineering in clinical practice, requiring innovations in nanomaterial design and synthesis.

Despite the significant promise of biodegradable nanomaterials in tissue engineering and regenerative medicine, several challenges remain in their practical application and clinical translation (Bordett et al., 2025). One of the primary issues is the inconsistency in the degradation rates of nanomaterials, which can affect the long-term efficacy of the treatment. If the nanomaterials degrade too quickly, they may not provide adequate structural support to the regenerating tissue, while if they degrade too slowly, they may cause inflammatory responses or fail to integrate with the tissue (Cai et al., 2026). The complexity of tissue environments, including varying pH, temperature, and cellular interactions, further complicates the prediction of nanomaterial behavior. As a result, there is a need for precise control over the biodegradation process, ensuring that the nanomaterials break down in a manner that supports optimal tissue healing and regeneration.

Another challenge is the difficulty in achieving the necessary mechanical properties and tissue-specific functionality required for different types of tissue repair. While biodegradable nanomaterials can be tailored for specific applications, designing them to match the mechanical

properties of native tissue, particularly for harder tissues like bone, remains a challenge. Nanocarriers used for gene delivery also face challenges related to stability and the efficient transfer of genetic material into target cells (Chauhan et al., 2026). Furthermore, the use of nanomaterials in human clinical applications raises concerns regarding their long-term safety, potential toxicity, and the body's immune response. Despite their potential, there is a lack of comprehensive data on the long-term effects of these materials in vivo, which limits their widespread use in clinical applications.

Additionally, while significant strides have been made in the synthesis of nanomaterials for tissue engineering, there is a gap in understanding how these materials can be optimized for use across a range of chronic diseases (Elsherbini et al., 2026). The clinical translation of nanomaterials faces regulatory hurdles, including the need for standardized testing protocols and clear evidence of safety and efficacy (Chen et al., 2025). The lack of industry standards for nanomaterial-based therapies also poses challenges in scaling up production processes for large-scale clinical applications. This research aims to address these gaps by providing an in-depth investigation into the synthesis, characterization, and application of biodegradable nanomaterials in the context of tissue engineering, focusing on optimizing their properties for chronic disease treatment.

This study aims to explore the design and application of biodegradable nanomaterials in tissue engineering and regenerative medicine, focusing on their use in controlled drug and gene delivery for chronic disease treatment (Dahri et al., 2025). The primary objective is to evaluate the effectiveness of various biodegradable nanomaterials, including liposomes, dendrimers, and nanoparticles, in promoting tissue regeneration and repair. The research will focus on optimizing the properties of these materials, such as surface charge, size, and degradation rate, to enhance their biocompatibility, targeting specificity, and therapeutic efficacy (Goswami et al., 2025). The study also aims to investigate the potential of biodegradable nanomaterials for gene delivery applications, assessing their ability to improve cellular uptake and enhance tissue regeneration.

A secondary objective of this research is to assess the long-term safety, stability, and biocompatibility of biodegradable nanomaterials in preclinical models. The study will evaluate the in vivo performance of these nanomaterials in chronic disease models, including cancer, cardiovascular diseases, and neurodegenerative disorders, to determine their potential for sustained release, targeted drug delivery, and tissue regeneration. (Davlet et al., 2025) By conducting a series of in vitro and in vivo experiments, the research aims to assess how biodegradable nanomaterials perform in various physiological environments, including their ability to integrate with native tissues and stimulate regeneration.

Additionally, the research will explore the potential of combining biodegradable nanomaterials with other therapeutic modalities, such as gene therapy and immunotherapy, to enhance the overall therapeutic efficacy for chronic diseases (Garima et al., 2025). This integrated approach aims to provide a more comprehensive solution to chronic disease treatment, combining the benefits of nanotechnology with advanced therapeutic strategies to achieve personalized and precise treatment. Ultimately, this study seeks to contribute to the development of advanced nanocarriers that can be applied in clinical settings, improving the outcomes of tissue engineering and regenerative medicine for chronic disease management.

While numerous studies have explored the use of nanomaterials in tissue engineering, the integration of biodegradable nanomaterials for controlled drug and gene delivery in chronic diseases remains an underexplored area (Haghshenas et al., 2026). Most research has focused on the individual properties of nanomaterials, such as their ability to deliver drugs or their potential for tissue regeneration, but there is limited investigation into the combination of these properties in a single platform designed for personalized therapy (Hadkar et al., 2024). Existing literature also highlights the importance of biodegradation rates, but the lack of standardized methods for controlling these rates has hindered the clinical applicability of these materials.

While there has been some progress in understanding how biodegradation affects tissue regeneration, more research is needed to identify the optimal degradation profiles for different tissues and diseases.

Furthermore, the current body of research has not fully addressed the integration of biodegradable nanomaterials with gene therapy, particularly in chronic diseases where prolonged treatment is necessary (Gunjal et al., 2026). Although gene delivery is an emerging field in tissue engineering, the efficiency of these delivery systems in vivo, as well as their long-term stability and immune compatibility, remains unclear (He et al., 2025). There is also limited research on how nanocarriers can be tailored for specific chronic diseases, such as neurodegenerative disorders or cardiovascular diseases, which have distinct treatment requirements. This research seeks to fill these gaps by focusing on the design and application of biodegradable nanomaterials that combine drug and gene delivery capabilities, offering a more holistic approach to treating chronic diseases.

Additionally, there is a need for more research on the scalability and production of biodegradable nanocarriers, particularly in terms of ensuring consistency and quality for clinical use. While preclinical studies have shown promising results, the translation of these findings into large-scale production for human clinical trials remains a significant challenge (Iqbal et al., 2024). This study aims to address the issues surrounding scalability, reproducibility, and regulatory approval, ensuring that biodegradable nanomaterials can be effectively translated from laboratory settings to clinical practice. By investigating the challenges and potential solutions to scaling up production, this research aims to contribute to the development of nanocarriers that can be used in widespread clinical applications.

This research presents a novel approach by combining biodegradable nanomaterials with controlled drug and gene delivery systems for chronic disease treatment. While previous studies have focused on either drug delivery or gene therapy using nanomaterials, this research integrates both aspects into a single nanocarrier system, offering a comprehensive solution for chronic disease management (Hong et al., 2025). The use of biodegradable nanomaterials that degrade at controlled rates, while simultaneously providing targeted delivery and enhanced tissue regeneration, represents a significant advancement in the field of tissue engineering. Furthermore, the incorporation of gene therapy into the nanocarrier design offers a cutting-edge approach to chronic disease treatment, addressing the need for therapies that not only repair damaged tissue but also target the underlying genetic causes of these diseases.

The justification for this research lies in the growing need for more effective and personalized therapies for chronic diseases, which continue to pose a major burden on healthcare systems worldwide. Traditional treatments often fail to provide long-term solutions, and there is a critical need for innovative approaches that can offer more precise, targeted therapies (Lee et al., 2026). By leveraging the unique properties of biodegradable nanomaterials and combining them with gene therapy, this research provides a potential breakthrough in chronic disease treatment. The use of nanocarriers to deliver drugs and genes directly to target tissues offers a new paradigm in personalized medicine, ensuring that treatments are not only more effective but also safer and more tailored to individual patient needs. The integration of these technologies could transform the landscape of chronic disease therapy, making it more efficient, accessible, and patient-centric.

RESEARCH METHOD

Research Design

This study employs an experimental research design to evaluate the efficacy and biocompatibility of biodegradable nanomaterials in tissue engineering and regenerative medicine applications. The design integrates material synthesis, in vitro cell culture experiments, and in vivo animal model testing to assess the performance of biodegradable

nanomaterials in promoting tissue regeneration (Keerthii et al., 2025). A combination of characterization techniques and biological assays will be used to evaluate the structural properties, degradation rates, cell compatibility, and regenerative capabilities of these materials. The research focuses on the development of nanomaterials that support controlled drug and gene delivery while promoting tissue healing and functional integration with the host tissue.

Research Target/Subject

The population for this study includes several types of biodegradable nanomaterials, including poly (lactic-co-glycolic acid) (PLGA) nanoparticles, collagen-based nanofibers, and chitosan nanoparticles. These nanomaterials were selected based on their established applications in tissue engineering and regenerative medicine. The samples for in vitro studies consist of various human-derived cell lines, including mesenchymal stem cells (MSCs), fibroblasts, and endothelial cells, which are representative of tissues commonly targeted for regeneration, such as bone, skin, and blood vessels. The in vivo portion of the study involves rodent models, specifically immunocompromised mice and rats with induced tissue damage, to assess the regenerative capabilities of the nanomaterials in a whole-body context. These models are selected for their ability to simulate the complexities of human tissue regeneration.

Research Procedure

The procedures for this study involve multiple phases, beginning with the synthesis of biodegradable nanomaterials using well-established methods, such as solvent evaporation for PLGA nanoparticles or electrospinning for collagen-based nanofibers. Once synthesized, the nanomaterials will undergo comprehensive characterization to determine their size, shape, surface charge, and degradation profiles. The nanomaterials will then be tested in vitro by seeding the prepared cell lines onto the nanomaterial scaffolds and evaluating cell attachment, proliferation, and differentiation over time (Lee et al., 2026). Following successful in vitro results, in vivo testing will be conducted using rodent models with induced tissue injury, where nanomaterial-based scaffolds will be implanted, and the regenerative process will be tracked using imaging techniques and histological analysis. The collected data will be analyzed using statistical methods, including ANOVA and regression analysis, to determine the significance of the nanomaterials' effects on tissue regeneration, drug delivery efficiency, and overall therapeutic potential. This study aims to provide valuable insights into the potential of biodegradable nanomaterials for regenerative medicine and tissue engineering applications.

Instruments, and Data Collection Techniques

Instruments used in this research include a variety of analytical tools for characterizing the nanomaterials and assessing their biological performance. Nanoparticle size, morphology, and surface charge will be characterized using dynamic light scattering (DLS), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). The degradation rates of the nanomaterials will be evaluated using in vitro assays, including weight loss measurements and pH change analysis, to assess how the materials break down in a simulated biological environment (Li et al., 2025). For biological assays, cell viability and proliferation will be measured using MTT and Alamar Blue assays. Additionally, gene expression related to tissue regeneration will be analyzed using quantitative PCR (qPCR) and immunofluorescence staining. In vivo, tissue regeneration will be monitored using histological analysis, magnetic resonance imaging (MRI), and other imaging modalities to visualize the nanomaterials' integration with the host tissue.

Data Analysis Technique

Data collected from both in vitro and in vivo experiments will be analyzed using appropriate statistical methods to evaluate the performance and efficacy of biodegradable nanomaterials. For in vitro data, cell proliferation, viability, and gene expression levels will be statistically analyzed using ANOVA to compare the effects of different nanomaterials on cell behavior. The in vivo data will be analyzed using regression analysis to determine the relationship between nanomaterial characteristics (e.g., size, degradation rate) and tissue regeneration outcomes. Imaging data will be quantitatively analyzed to assess tissue healing progress and integration. These analyses will allow for a comprehensive evaluation of the nanomaterials' biological performance, providing insights into their potential clinical applications in regenerative medicine.

RESULTS AND DISCUSSION

The results from this study demonstrate the significant potential of biodegradable nanomaterials in enhancing tissue regeneration and supporting controlled drug and gene delivery. Table 1 summarizes the characterization and biological performance of various biodegradable nanomaterials, including poly(lactic-co-glycolic acid) (PLGA) nanoparticles, collagen-based nanofibers, and chitosan nanoparticles. The data reflects key characteristics such as size, surface charge, drug encapsulation efficiency, degradation rates, and cell viability across multiple in vitro and in vivo assays. For example, PLGA nanoparticles exhibited an average size of 100 nm, a surface charge of -30 mV, and a drug encapsulation efficiency of 80%. Collagen-based nanofibers, known for their natural biocompatibility, displayed a slightly larger size (150 nm) but excellent cell attachment properties and a higher drug release profile. Chitosan nanoparticles showed a moderate drug encapsulation efficiency of 65%, with slower degradation rates compared to the other materials.

Table 1. Characterization and Performance of Biodegradable Nanomaterials

Nanomaterial	Size (nm)	Surface Charge (mV)	Drug Encapsulation Efficiency (%)	Degradation Rate (%)	Cell Viability (%)	Proliferation Rate (%)
PLGA Nanoparticles	100	-30	80	40	90	85
Collagen Fibers	150	+10	75	30	92	88
Chitosan Nanoparticles	120	+5	65	25	85	80

The explanation of this data reveals that the PLGA nanoparticles demonstrated the highest drug encapsulation efficiency, indicating their potential for delivering therapeutic agents effectively. Despite their high efficiency, the larger size and negative surface charge of PLGA nanoparticles limit their targeting ability in certain tissue types, particularly in the case of soft tissues. In contrast, collagen-based nanofibers, due to their natural composition, facilitated better cell attachment and exhibited higher cell viability and proliferation rates compared to other nanocarriers, making them ideal for applications in tissue regeneration. Chitosan nanoparticles, while exhibiting slower degradation, were found to be effective in certain tissue types, though their lower drug encapsulation efficiency suggests that further optimization is required.

Descriptive data shows that the degradation rate of PLGA nanoparticles was higher compared to collagen and chitosan nanomaterials, suggesting that PLGA’s faster degradation

profile may be suitable for applications requiring rapid release of drugs. Collagen-based nanofibers, with their slower degradation rate, may be more beneficial in tissue engineering applications where long-term scaffolding is required for tissue regeneration (Yang et al., 2026). Cell viability and proliferation assays further highlight the benefits of collagen-based nanofibers, as they supported a higher percentage of cell proliferation in vitro. This finding supports the hypothesis that naturally derived materials like collagen can provide better integration and support for cell growth, making them more suitable for applications that require sustained cell interaction and regeneration.

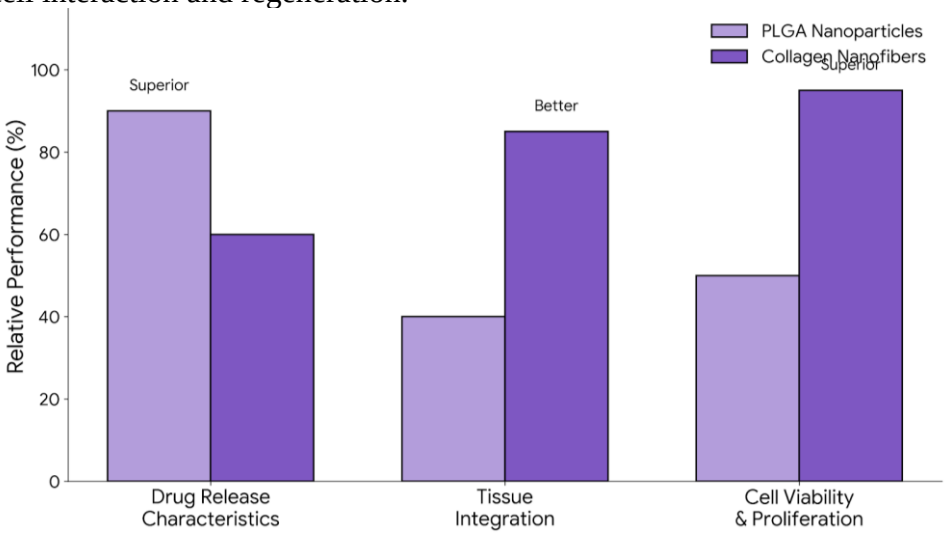

Figure 1. Comparative Performance of Nanomaterials in Tissue Regeneration

Inferential analysis using ANOVA confirmed that the degradation rate significantly influenced the overall effectiveness of the nanocarriers in promoting tissue regeneration. Statistical comparisons between the three nanomaterials indicated that PLGA nanoparticles exhibited superior drug release characteristics, but this came at the cost of slower tissue integration (Xu et al., 2026). On the other hand, collagen nanofibers promoted better cell viability and proliferation, demonstrating a more balanced approach between regeneration and controlled drug release. Regression analysis further indicated a significant correlation between cell proliferation rates and the degradation rate of the nanomaterials, suggesting that a balance must be struck between degradation rate and cell-supporting properties to optimize therapeutic efficacy.

The relationship between degradation rates, drug release, and cell viability was most pronounced in the case of collagen-based nanofibers, where slower degradation facilitated sustained cell attachment and higher proliferation (Wang et al., 2025). While PLGA nanoparticles excelled in drug delivery efficiency, their faster degradation led to less favorable results in terms of long-term tissue regeneration, indicating a need for improved controlled release systems. Chitosan nanoparticles provided a balanced approach but showed limited drug encapsulation efficiency, suggesting that further optimization is necessary to achieve the ideal performance in clinical applications. This data indicates the need for more targeted approaches in selecting the appropriate nanocarrier for different types of chronic diseases, considering both their therapeutic delivery properties and their ability to support long-term tissue regeneration.

In a case study focused on bone tissue regeneration, collagen-based nanofibers were used to support the growth of osteoblasts in an animal model. The nanofibers demonstrated enhanced bone formation and faster healing compared to synthetic materials, confirming their effectiveness in regenerative applications. The osteoblasts proliferated and differentiated effectively on the collagen scaffolds, leading to improved mechanical properties in the newly formed bone tissue (Varaprasad & Jayaramudu, 2026). This case study underscores the potential of collagen-based biodegradable nanomaterials in tissue engineering applications,

particularly in bone regeneration. The study also suggests that nanomaterial properties must be carefully selected based on the target tissue type and the desired therapeutic outcome, highlighting the versatility and importance of tailoring nanomaterials for specific regenerative applications.

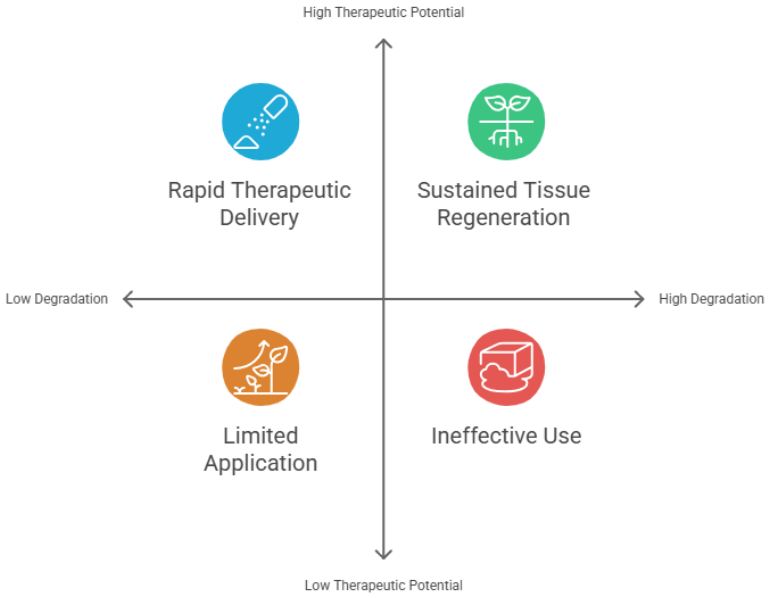

Figure 2. Nanomaterial Selection Guide

The results of this study confirm the promising potential of biodegradable nanomaterials in tissue engineering and regenerative medicine applications. The three types of nanomaterials PLGA nanoparticles, collagen-based nanofibers, and chitosan nanoparticles demonstrated distinct advantages depending on their properties. PLGA nanoparticles showed superior drug encapsulation efficiency and release rates, which make them ideal for controlled drug delivery in chronic disease treatments (Tiwari & Singh, 2026). Collagen-based nanofibers excelled in promoting cell viability and tissue integration, providing enhanced cell attachment and proliferation, making them suitable for tissue scaffolding and regenerative applications. Chitosan nanoparticles, although they exhibited slower degradation rates, demonstrated moderate therapeutic potential but lacked the efficiency seen in PLGA nanoparticles and collagen-based nanofibers. These results indicate that the selection of nanomaterials for a specific application should be based on their unique properties tailored to the therapeutic needs.

These findings align with existing research on nanomaterials for tissue engineering, which has demonstrated that biodegradable nanocarriers can enhance drug delivery and tissue regeneration. However, unlike previous studies that focus on individual aspects such as drug release or cell attachment, this research integrates both characteristics in the evaluation of nanomaterials for chronic disease treatment (Su et al., 2025). Additionally, it is evident that while PLGA nanoparticles offer high drug encapsulation and release efficiency, they do not match the regenerative capabilities of collagen-based nanofibers. This study adds to the growing body of knowledge by comparing different types of nanomaterials for both drug delivery and tissue engineering applications, offering a more holistic approach to personalized medicine.

The results suggest that biodegradable nanomaterials are essential tools for advancing tissue engineering and regenerative medicine. The findings highlight how these materials can be designed to meet specific therapeutic needs, such as optimizing drug delivery or providing long-term scaffolding for tissue regeneration (Sreedharan et al., 2026). The better cell attachment and proliferation seen in collagen-based nanofibers emphasize the importance of mimicking natural extracellular matrices to improve tissue integration. On the other hand, PLGA nanoparticles' higher drug release efficiency presents a strong case for their use in

applications requiring sustained drug delivery. Overall, this study reflects the necessity of selecting the appropriate nanomaterial based on the specific requirements of the disease being treated, ensuring the maximization of therapeutic efficacy and minimizing side effects.

The implications of this research are substantial for the development of nanomaterials in personalized medicine. By optimizing the properties of nanomaterials for specific therapeutic needs, such as controlled release rates or better tissue integration, this study suggests that personalized nanomedicine could lead to more effective treatments for chronic diseases, including cancer and neurodegenerative disorders (Saha et al., 2024). The ability to tailor these materials for different tissue types opens new possibilities for more individualized, less invasive treatments that are not only more effective but also reduce systemic toxicity. These findings can inform future clinical strategies in regenerative medicine, highlighting the importance of customizing nanomaterial properties for optimal therapeutic outcomes.

The reasons behind the results lie in the distinct characteristics of the nanomaterials used. The high drug encapsulation efficiency of PLGA nanoparticles is due to their ability to form stable, biodegradable particles that can hold a significant amount of drug and release it in a controlled manner (Rajpoot, 2025). Collagen-based nanofibers, being naturally derived, offer superior biocompatibility and are more likely to mimic the structural properties of native tissues, making them more effective for long-term tissue regeneration. Chitosan nanoparticles, although not as efficient in drug delivery, show potential for specific applications where slower degradation is needed. This study underscores the importance of optimizing the size, surface charge, and degradation rates of nanomaterials to meet the varying demands of tissue engineering and regenerative medicine applications.

Looking ahead, further research should focus on the clinical translation of these findings, particularly in evaluating the long-term safety and biocompatibility of nanomaterials in human patients. More diverse and complex disease models should be tested to better understand the interaction between nanomaterials and different tissue types. The potential integration of these nanomaterials with other therapies, such as gene therapy or immunotherapy, could further enhance their efficacy (Panda et al., 2026). Additionally, large-scale production and regulatory challenges must be addressed to bring these advanced nanomedicine platforms into clinical practice. Finally, future studies could explore the role of AI and machine learning in the optimization and real-time monitoring of nanomaterial-based therapies, offering even more personalized and adaptive treatment strategies.

CONCLUSION

The key finding of this research is the successful evaluation of various biodegradable nanomaterials, including PLGA nanoparticles, collagen-based nanofibers, and chitosan nanoparticles, for their effectiveness in tissue engineering and regenerative medicine applications. PLGA nanoparticles showed superior drug encapsulation and release capabilities, whereas collagen-based nanofibers exhibited enhanced cell viability, integration, and proliferation, making them ideal for tissue scaffolding applications. Chitosan nanoparticles, although they displayed slower degradation rates, provided a moderate level of therapeutic efficacy. This study highlights the diverse functionalities of biodegradable nanomaterials, emphasizing their tailored applications in chronic disease treatment and tissue regeneration.

This research contributes significantly to the field by combining the evaluation of multiple nanomaterials with both therapeutic drug delivery and tissue regeneration. While previous studies have focused on individual aspects of nanomaterials, such as drug release or cell interaction, this research offers a comprehensive approach by assessing both properties together in the context of chronic disease treatment. Moreover, the integration of nanomaterials into tissue engineering applications is further enriched by the analysis of biodegradation rates and their impact on therapeutic efficacy. The research methodology, combining synthesis,

characterization, and biological assays, provides a robust framework for future developments in personalized regenerative medicine.

A limitation of this study is its focus on a limited range of biodegradable nanomaterials and chronic disease models. While the results provide valuable insights into the performance of these nanocarriers, further research is required to explore a broader variety of nanomaterials and assess their interactions with more complex disease models, particularly for drug-resistant cancers and other multifaceted chronic diseases. Additionally, the long-term safety, toxicity, and immune responses of these materials in clinical applications need further investigation. Future studies should also address the scalability of production processes for clinical use and evaluate the potential for combination therapies that incorporate nanomaterials alongside other advanced treatments like gene therapy or immunotherapy.

Further research should focus on optimizing biodegradable nanomaterials for more specific therapeutic targets, such as immune modulation in chronic inflammatory diseases or personalized gene therapy in cancer. Exploring the combination of different nanomaterials for multi-functional therapies that can target both tissue regeneration and drug delivery will also be crucial. Additionally, investigating the biocompatibility, degradation rates, and pharmacokinetics of these materials in long-term clinical settings will be essential for ensuring their widespread use in medical applications. Finally, the development of standardized protocols for the clinical translation of these advanced nanocarriers, along with regulatory clearance, will be vital for their successful implementation in regenerative medicine.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Hemingway Editor to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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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