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Smart Nanomaterials for Targeted Stem Cell Modulation: Safety, Efficacy and GMP Compliance

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Abstract

Smart nanomaterials have emerged as a promising strategy to enhance the therapeutic potential of stem cell based regenerative medicine. Among these, stimuli-responsive nanocarriers offer precise spatiotemporal control over drug delivery and cellular modulation by responding to specific biological or physicochemical triggers such as pH, temperature, enzymes, and redox gradients. These advanced systems improve stem cell homing, survival, differentiation, and immunomodulatory functions while minimizing systemic toxicity. Despite their significant advantages, concerns related to safety, including cytotoxicity, immunogenicity, biodistribution, and long-term toxicity, remain critical barriers to clinical translation. Furthermore, the integration of nanotechnology with stem cell therapy introduces additional complexity in manufacturing, requiring strict adherence to Good Manufacturing Practice (GMP) standards to ensure product quality, reproducibility, and safety. This review critically evaluates the design, mechanisms, efficacy, and safety of responsive nanocarriers for targeted stem cell modulation. It also examines current GMP requirements, regulatory challenges, and translational hurdles associated with these hybrid systems. Finally, future perspectives focusing on scalable manufacturing, standardized regulatory frameworks, and advanced biomimetic nanomaterials are discussed to accelerate clinical adoption.

Keywords: Smart nanomaterials, Stem cell modulation, Responsive nanocarriers, Regenerative medicine, Nanotoxicity, GMP compliance

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1. Introduction

Regenerative medicine aims to restore or replace damaged tissues and organs by harnessing the therapeutic potential of stem cells [1, 2]. Stem cells, including mesenchymal stem cells (MSCs), embryonic stem cells (ESCs), and induced pluripotent stem cells (iPSCs), possess the unique ability to self-renew and differentiate into multiple cell lineages. These properties make them highly attractive for treating a wide range of diseases, including neurodegenerative disorders, cardiovascular diseases, and musculoskeletal injuries. However, conventional stem cell therapies face several limitations, such as poor cell survival, low engraftment efficiency, immune rejection, and lack of targeted delivery [3].

In recent years, nanotechnology has emerged as a powerful tool to overcome these challenges. Smart nanomaterials, particularly stimuli-responsive nanocarriers, have demonstrated significant potential in enhancing the efficacy of stem cell therapies [4, 5]. These nanocarriers are engineered to respond to specific internal or external stimuli, enabling controlled release of therapeutic agents and precise modulation of stem cell behaviour [6, 7]. By improving cell targeting, protecting therapeutic payloads, and regulating the cellular microenvironment, responsive nanocarriers can significantly enhance regenerative outcomes[5].

Despite these advancements, the clinical translation of smart nanomaterials remains limited due to safety concerns and manufacturing challenges. The interaction of nanomaterials with biological systems can lead to unintended toxicological effects, including inflammation, oxidative stress, and long-term accumulation in vital organs [8]. Moreover, the production of nanocarrier-based stem cell therapies requires compliance with stringent GMP standards to ensure consistency, quality, and safety [9].

This review aims to provide a comprehensive overview of smart nanomaterials for targeted stem cell modulation, with a focus on their design principles, mechanisms of action, therapeutic efficacy, safety considerations, and alignment with GMP requirements. Understanding these aspects is essential for advancing the development of safe and effective nanotechnology-based regenerative therapies.

2. Smart Nanomaterials: Classification and Design Principles

2.1 Types of Nanomaterials

Smart nanomaterials used in stem cell modulation can be broadly classified based on their composition and structure.

Liposomes are lipid-based vesicles capable of encapsulating both hydrophilic and hydrophobic agents. Their biocompatibility and ability to fuse with cell membranes make them suitable for drug

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delivery in stem cell applications [10].

Polymeric nanoparticles are widely used due to their tenable properties, controlled degradation, and versatility. Biodegradable polymers such as PLGA and chitosan allow sustained release of therapeutic agents [11].

Dendrimers are highly branched nanostructures with a well-defined architecture, offering high drug-loading capacity and precise functionalization [12].

Inorganic nanoparticles including gold, silica, and magnetic nanoparticles, provide unique optical, electrical, and magnetic properties that can be exploited for imaging and targeted delivery [13].

Table 1. Types of Smart Nanomaterials and Their Key Characteristics in Stem Cell Modulation

Nanomaterial Type	Composition	Key Properties	Advantages	Limitations	Applications in Stem Cell Modulation	Reference
Liposomes	Phospholipid bilayer vesicles	Biocompatible, amphiphilic	Can encapsulate hydrophilic & hydrophobic drugs	Stability issues, leakage	Drug delivery, cell membrane fusion	[10]
Polymeric Nanoparticles	PLGA, chitosan, PEG	Biodegradable, tenable release	Controlled drug release, high stability	Complex synthesis	Sustained delivery of growth factors	[11]
Dendrimers	Branched polymers	High surface functionality	High drug loading, precise targeting	Potential toxicity	Gene delivery, stem cell differentiation	[12]

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Inorganic Nanoparticles	Gold, silica, iron oxide	Optical, magnetic properties	Imaging + therapy (theragnostic)	Non-biodegradable, accumulation	Cell tracking, targeted delivery	[13]
Biomimetic Nanoparticles	Cell membrane-coated systems	Immune evasion, biomimicry	Long circulation, low immunogenicity	Complex fabrication	Targeted delivery, immune modulation	[14]

2.2 Stimuli-Responsive Mechanisms

A defining feature of smart nanocarriers is their ability to respond to environmental stimuli.

- **pH-responsive systems;** release their payload in acidic environments, such as inflamed or tumour tissues [5].
- **Temperature-sensitive nanocarriers;** respond to localized heating, enabling controlled drug release[15] .
- **Enzyme-responsive systems;** utilize disease-specific enzymes to trigger drug releasem [16].
- **Redox-responsive nanocarriers;** exploit intracellular redox gradients for targeted delivery [17].

These mechanisms enable site-specific drug release and minimize off-target effects.

2.3 Surface Functionalization and Targeting Strategies

Surface modification plays a crucial role in enhancing the specificity and efficiency of nanocarriers.

- **Ligand-mediated targeting** involves attaching ligands that bind to receptors on stem cells or target tissues [18].
- **Antibody-functionalized nanoparticles** provide high specificity for targeted delivery [16, 18].

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- **Biomimetic coatings** such as cell membrane cloaking, improve biocompatibility and immune evasion [14].

Such strategies enhance cellular uptake and improve therapeutic outcomes.

3. Mechanisms of Stem Cell Modulation by Nanocarriers

Smart nanocarriers play a pivotal role in modulating stem cell behaviour by enabling targeted delivery of bioactive molecules, improving cellular interactions, and regulating the local microenvironment. These multifunctional systems enhance the therapeutic efficiency of stem cell–based regenerative medicine through several interconnected mechanisms.

3.1 Enhancement of Stem Cell Homing and Engraftment

One of the major limitations of stem cell therapy is the poor homing efficiency and low retention of transplanted cells at the target site. After systemic administration, only a small fraction of stem cells reaches the injured tissue, significantly reducing therapeutic efficacy. Nanocarriers address this challenge by enhancing the targeting ability of stem cells. This can be achieved through surface functionalization with specific ligands or antibodies that recognize receptors expressed on damaged tissues [19]. Additionally, nanocarriers can deliver chemokines or signalling molecules that guide stem cell migration. These strategies improve cell adhesion, migration, and retention, leading to enhanced engraftment and better regenerative outcomes.

3.2 Controlled Differentiation and Proliferation

Another critical mechanism is the regulation of stem cell differentiation and proliferation. Responsive nanocarriers can encapsulate and deliver growth factors, transcription factors, and nucleic acids such as DNA and siRNA. Upon exposure to specific stimuli, these nanocarriers release their payload in a controlled manner, directing stem cells toward desired lineages. For example, osteogenic factors promote differentiation into bone-forming cells, while neurotrophic factors support neural differentiation. Controlled release ensures sustained signalling, preventing premature degradation of therapeutic agents and improving efficiency. Moreover, nanocarriers can regulate cell proliferation by modulating intracellular signalling pathways, ensuring optimal cell expansion without uncontrolled growth [20].

3.3 Immunomodulatory Effects

The immune response plays a crucial role in determining the success of stem cell therapies. Inflammatory environments can reduce stem cell survival and impair regeneration. Nanocarriers contribute to immunomodulation by delivering anti-inflammatory drugs, cytokines, or immunosuppressive agents directly to the target site. This localized delivery minimizes systemic

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side effects while creating a favourable environment for stem cell survival and integration [21]. Furthermore, certain nanomaterials can inherently modulate immune responses by interacting with immune cells and reducing the production of pro-inflammatory cytokines. This immunoregulatory function enhances tissue repair and reduces the risk of immune rejection.

3.4 Microenvironment Engineering

The stem cell microenvironment, or niche, is a key determinant of cell fate and function. Nanocarriers can be designed to mimic or modify this microenvironment by providing both biochemical and physical cues. For instance, nanomaterials can replicate components of the extracellular matrix, supporting cell adhesion and growth. They can also deliver signalling molecules that regulate cell behaviour in a spatially and temporally controlled manner. Additionally, nanocarriers can influence mechanical properties such as stiffness, which plays a role in directing stem cell differentiation [22]. By engineering a supportive and dynamic microenvironment, nanocarriers enhance stem cell viability, functionality, and regenerative potential (Figure 1).

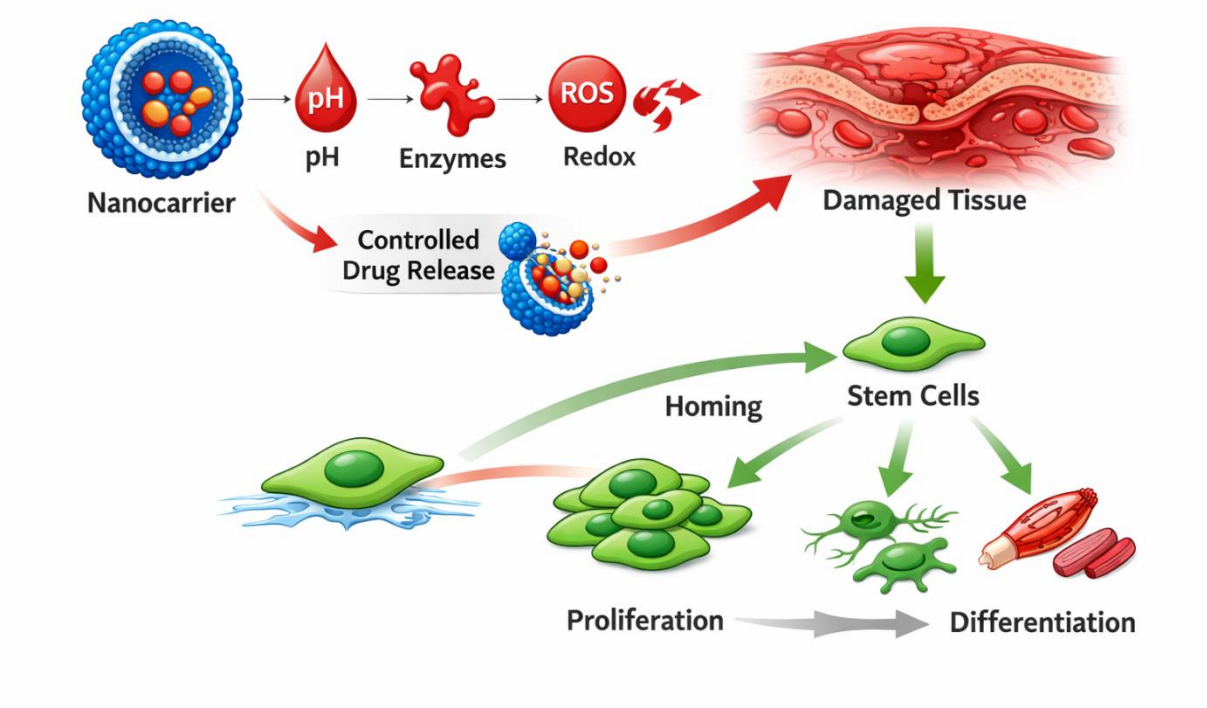

Figure 1. Schematic representation of stimuli-responsive nanocarriers for targeted stem cell modulation

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4. Efficacy of Responsive Nanocarriers in Regenerative Medicine

Responsive nanocarriers have emerged as a powerful strategy to enhance the therapeutic efficacy of stem cell based regenerative medicine by enabling targeted delivery, controlled release, and improved cellular interactions. These systems address critical limitations of conventional therapies, including poor cell survival, inefficient targeting, and lack of controlled therapeutic action. By responding to specific physiological stimuli, such as pH, enzymes, and redox conditions, nanocarriers provide spatiotemporal control over drug release, thereby improving regeneration outcomes.

4.1 Tissue Engineering Applications

Responsive nanocarriers have shown significant promise in various tissue engineering applications, particularly in bone, neural, and cardiac regeneration.

In bone and cartilage regeneration, nanocarriers are widely used to deliver osteogenic and chondrogenic factors that promote the differentiation of mesenchymal stem cells into osteoblasts and chondrocytes. Controlled release of growth factors such as bone morphogenetic proteins (BMPs) enhances matrix deposition, accelerates healing, and improves the structural integrity of regenerated tissues. Additionally, nanomaterials can mimic the extracellular matrix, providing mechanical support and biochemical cues essential for tissue formation [23].

In neural tissue repair, responsive nanocarriers facilitate the delivery of neurotrophic factors and anti-inflammatory agents to damaged neural tissues. These systems support neuronal survival, axonal growth, and synaptic plasticity, which are critical for functional recovery in conditions such as spinal cord injury and neurodegenerative diseases [24]. The ability to cross biological barriers, such as the blood–brain barrier, further enhances their therapeutic potential.

In cardiac regeneration, nanocarriers improve the retention and survival of stem cells in ischemic heart tissue. By delivering angiogenic factors, these systems promote neovascularization and tissue repair, leading to improved cardiac function. Injectable nanocarrier systems also provide a supportive microenvironment that enhances cell integration and reduces apoptosis [25].

4.2 Drug and Gene Delivery Systems

Responsive nanocarriers play a crucial role in the efficient delivery of therapeutic agents.

For growth factor delivery, nanocarriers protect bioactive molecules from degradation and enable their sustained and localized release. This controlled delivery enhances bioavailability and reduces the need for repeated administration [26].

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In gene delivery applications, nanocarriers facilitate the transport of nucleic acids such as siRNA, mRNA, and DNA into stem cells. SiRNA-loaded nanoparticles can silence specific genes that inhibit regeneration, while advanced gene-editing tools, including CRISPR-Cas systems, allow precise genetic modification. These approaches enable targeted regulation of stem cell behaviour, improving therapeutic outcomes and opening new avenues for personalized medicine [27].

4.3 Preclinical and Clinical Evidence

The efficacy of responsive nanocarriers has been extensively demonstrated in preclinical studies.

In vitro studies have shown enhanced stem cell viability, proliferation, and differentiation when combined with nanocarrier systems. These studies highlight the ability of nanomaterials to provide controlled microenvironments and efficient intracellular delivery of therapeutic agents [20].

In vivo animal models further confirm these findings, demonstrating improved tissue regeneration, reduced inflammation, and enhanced functional recovery in various disease models. Nanocarrier-assisted therapies have shown superior performance compared to conventional stem cell treatments in models of bone defects, neural injury, and myocardial infarction [23].

Emerging clinical trials suggest that these systems are generally safe and well tolerated, with early evidence of improved therapeutic efficacy. However, large-scale clinical validation is still required to establish long-term safety and effectiveness [28].

5. Safety and Toxicological Considerations

The clinical translation of responsive nanocarriers in stem cell–based regenerative medicine is critically dependent on their safety profile. While these systems offer enhanced therapeutic efficacy, their interaction with biological systems can introduce potential toxicological risks that must be carefully evaluated through comprehensive preclinical and clinical studies.

5.1 Cytotoxicity and Biocompatibility

Cytotoxicity is one of the primary concerns associated with nanomaterials and is influenced by factors such as particle size, shape, surface charge, composition, and concentration. Smaller nanoparticles often exhibit higher cellular uptake but may also generate increased reactive oxygen species (ROS), leading to oxidative stress and cellular damage [9] Surface charge also plays a crucial role, as positively charged nanoparticles tend to interact more strongly with cell membranes, potentially causing membrane disruption. To mitigate these effects, the use of biocompatible and biodegradable materials such as lipids and polymers is preferred. Surface modifications, including PEGylation and biomimetic coatings, further enhance compatibility and reduce toxicity [8].

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5.2 Immunogenicity and Inflammatory Responses

Nanocarriers can trigger immune responses, which may compromise stem cell survival and therapeutic efficacy. Activation of the immune system can lead to the release of pro-inflammatory cytokines, complement activation, and hypersensitivity reactions. These responses are often dependent on nanoparticle composition and surface properties. Strategies such as surface functionalization with hydrophilic polymers or cell membrane coatings are employed to reduce immune recognition and prolong circulation time. Achieving an optimal balance between immune evasion and therapeutic activity is essential for safe clinical application [21] .

5.3 Biodistribution and Clearance

The in vivo distribution and clearance of nanocarriers significantly influence their safety and effectiveness. After administration, nanoparticles are often recognized and cleared by the reticuloendothelial system, leading to accumulation in organs such as the liver, spleen, and lungs. This accumulation may result in organ-specific toxicity, particularly with non-biodegradable materials. Designing nanoparticles with optimal size, shape, and surface characteristics can improve their circulation time and reduce unwanted accumulation. Additionally, biodegradable nanocarriers that can be metabolized and excreted are preferred to minimize long-term risks [29].

5.4 Long-Term Toxicity and Genotoxicity

Long-term exposure to nanomaterials raises concerns regarding chronic toxicity and genotoxic effects. Persistent nanoparticles may induce oxidative stress, inflammation, and DNA damage, potentially leading to mutations or carcinogenesis. These risks are particularly important in regenerative medicine, where therapies may involve prolonged or repeated exposure. Therefore, long-term in vivo studies and careful monitoring are essential to assess the potential cumulative effects of nanocarriers [8].

5.5 Stem Cell–Specific Safety Concerns

Tumorigenicity

One of the most critical risks in stem cell therapy is tumour formation. The use of pluripotent stem cells, such as embryonic or induced pluripotent stem cells, carries a risk of uncontrolled growth and teratoma formation. Nanocarriers that influence cell proliferation or gene expression must be carefully designed to avoid enhancing this risk [28].

Uncontrolled Differentiation

Another concern is the possibility of unintended or incomplete differentiation of stem cells, which can result in the formation of inappropriate tissue types. Nanocarriers delivering growth factors or

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genetic material must ensure precise control over differentiation pathways to prevent adverse outcomes [29].

6. GMP (Good Manufacturing Practice) Considerations

The successful clinical translation of responsive nanocarrier based stem cell therapies rely heavily on strict adherence to Good Manufacturing Practice (GMP) standards. GMP ensures that products are consistently produced and controlled according to quality standards appropriate for their intended use. Given the complexity of combining nanomaterials with living cells, maintaining quality, safety, and reproducibility presents unique challenges[9, 29] .

6.1 Regulatory Frameworks and Guidelines

Regulatory agencies such as the FDA and EMA have established GMP guidelines for advanced therapy medicinal products (ATMPs), including cell-based and nanotechnology-driven therapies. These frameworks emphasize stringent control over raw materials, manufacturing processes, quality assurance, and documentation [9]. However, responsive nanocarriers integrated with stem cells often fall into a hybrid category, making regulatory classification more complex. As a result, products are frequently evaluated on a case-by-case basis, highlighting the need for more specific and harmonized guidelines for nanomedicine [29].

6.2 Manufacturing Challenges

Scalability

Scaling up the production of nanocarriers from laboratory to industrial levels is a major challenge. Techniques that work efficiently at a small scale may not maintain consistency when applied to large-scale manufacturing. Parameters such as particle size, drug loading efficiency, and release kinetics must remain uniform across batches to meet regulatory requirements [4, 29].

Reproducibility

Achieving batch-to-batch reproducibility is essential for GMP compliance. Variations in synthesis conditions, raw materials, and processing methods can lead to inconsistencies in nanoparticle properties. When combined with stem cells, variability in cell source, culture conditions, and handling further complicates reproducibility [6, 29].

6.3 Quality Control and Characterization

Physicochemical Properties

Comprehensive characterization of nanocarriers is critical to ensure product quality. Key parameters include particle size and distribution, surface charge (zeta potential), morphology, encapsulation

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efficiency, and release profiles. Advanced analytical techniques such as dynamic light scattering (DLS), electron microscopy, and spectroscopy are commonly used for this purpose [4, 11].

Sterility and Endotoxin Testing

Sterility is a fundamental requirement for all injectable therapies. Nanocarrier–stem cell products must undergo rigorous sterility testing to prevent microbial contamination. Endotoxin levels must also be carefully monitored, as even small amounts can trigger severe immune responses. Aseptic processing and cleanroom environments are essential to maintain product safety [8, 9].

6.4 Process Validation and Documentation

GMP compliance requires thorough validation of all manufacturing processes to ensure consistency and reliability. This includes establishing standard operating procedures (SOPs), validating critical process parameters, and maintaining detailed batch records. Documentation ensures traceability and facilitates regulatory review. Additionally, in-process monitoring and quality assurance systems are implemented to detect and correct deviations during production [9, 29].

6.5 Challenges in Hybrid Systems (Nanocarrier + Stem Cells)

Hybrid systems combining nanocarriers with stem cells introduce additional complexity. Maintaining cell viability during nanoparticle loading and processing is a major concern. Ensuring uniform distribution of nanocarriers within or on stem cells is also challenging [3]. Furthermore, these products must meet both biologic and nanomaterial regulatory requirements, increasing the burden of validation and approval (Figure 2)

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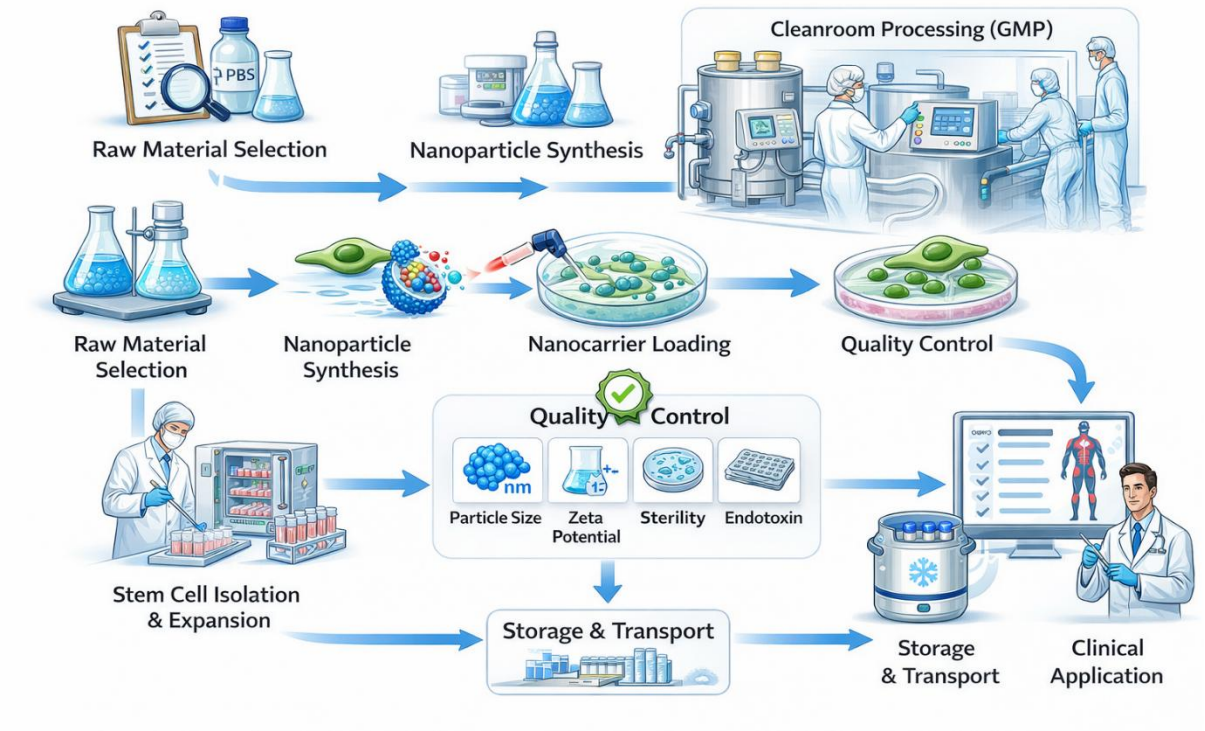

Figure 2. GMP-compliant manufacturing and quality control workflow for nanocarrier-based stem cell therapies

7. Translational and Regulatory Challenges

Despite significant advancements in smart nanomaterials, their translation from laboratory research to clinical practice remains limited due to multiple regulatory and practical challenges. One of the major issues is the lack of standardized regulatory frameworks specifically tailored for nanomedicine. Currently, responsive nanocarriers used in stem cell therapies are often evaluated under existing guidelines for biologics or drug delivery systems, which may not fully address their hybrid and multifunctional nature [9].

Another critical challenge is variability in preclinical models and experimental protocols. Differences in animal models, dosing strategies, and evaluation methods make it difficult to compare results across studies and hinder reproducibility. This variability can delay regulatory approval and clinical adoption [29].

Additionally, scalability and manufacturing costs pose significant barriers. Producing nanocarrier-based stem cell therapies at an industrial scale while maintaining consistency and quality is complex and expensive. Regulatory agencies also require extensive safety and efficacy data, further increasing development time and cost.

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Ethical considerations related to stem cell sourcing and manipulation also play a role in regulatory decision-making. Addressing these challenges requires the development of harmonized global guidelines, standardized testing protocols, and collaborative efforts between researchers, industry, and regulatory bodies.

8. Future Perspectives and Emerging Trends

The future of smart nanomaterials in regenerative medicine is highly promising, driven by rapid advancements in material science, biotechnology, and computational tools. One of the most significant emerging trends is the use of artificial intelligence (AI) to design and optimize nanocarriers with improved targeting efficiency, stability, and controlled release properties. AI-driven models can accelerate the discovery of novel materials and reduce experimental costs.

Another important development is the shift toward personalized regenerative therapies, where nanocarrier systems are tailored to individual patient profiles, enhancing therapeutic outcomes and minimizing adverse effects. Biomimetic nanomaterials, such as exosome-based delivery systems, are also gaining attention due to their natural origin, biocompatibility, and reduced immunogenicity.

Furthermore, the integration of nanotechnology with gene-editing tools, such as CRISPR-Cas systems, opens new possibilities for precise genetic modulation of stem cells. Advances in 3D bioprinting and tissue engineering are also expected to benefit from smart nanomaterials, enabling the development of complex, functional tissues.

Overall, continued interdisciplinary research and technological innovation will play a crucial role in overcoming current limitations and accelerating the clinical translation of these advanced therapeutic systems.

9. Conclusion

Smart nanomaterials, particularly stimuli-responsive nanocarriers, represent a transformative advancement in the field of regenerative medicine. By enabling targeted delivery, controlled release, and precise modulation of stem cell behaviour, these systems address many of the limitations associated with conventional stem cell therapies. Their ability to enhance cell homing, survival, differentiation, and immunomodulation significantly improves therapeutic efficacy.

However, the successful clinical translation of these technologies requires careful consideration of safety concerns, including cytotoxicity, immunogenicity, biodistribution, and long-term effects. In addition, compliance with Good Manufacturing Practice (GMP) standards is essential to ensure product quality, reproducibility, and regulatory approval.

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Despite existing challenges related to scalability, standardization, and regulatory complexity, ongoing advancements in nanotechnology, biomaterials, and computational design are expected to drive progress in this field. Future efforts should focus on developing safer, more efficient, and clinically scalable systems.

In conclusion, smart nanocarriers hold immense potential to revolutionize regenerative medicine, provided that innovation is balanced with rigorous safety evaluation and robust manufacturing practices.

Conflict of Interest: None

References

[1] J. Shi, P. W. Kantoff, R. Wooster, and O. C. Farokhzad, "Cancer nanomedicine: progress, challenges and opportunities," (in eng), *Nat Rev Cancer,* vol. 17, no. 1, pp. 20-37, Jan 2017, doi: 10.1038/nrc.2016.108.

[2] A. Trounson and C. McDonald, "Stem Cell Therapies in Clinical Trials: Progress and Challenges," (in eng), *Cell Stem Cell,* vol. 17, no. 1, pp. 11-22, Jul 2 2015, doi: 10.1016/j.stem.2015.06.007.

[3] J. Galipeau and L. Sensébé, "Mesenchymal Stromal Cells: Clinical Challenges and Therapeutic Opportunities," (in eng), *Cell Stem Cell,* vol. 22, no. 6, pp. 824-833, Jun 1 2018, doi: 10.1016/j.stem.2018.05.004.

[4] M. J. Mitchell, M. M. Billingsley, R. M. Haley, M. E. Wechsler, N. A. Peppas, and R. Langer, "Engineering precision nanoparticles for drug delivery," (in eng), *Nat Rev Drug Discov,* vol. 20, no. 2, pp. 101-124, Feb 2021, doi: 10.1038/s41573-020-0090-8.

[5] S. Mura, J. Nicolas, and P. Couvreur, "Stimuli-responsive nanocarriers for drug delivery," (in eng), *Nat Mater,* vol. 12, no. 11, pp. 991-1003, Nov 2013, doi: 10.1038/nmat3776.

[6] A. C. Anselmo and S. Mitragotri, "Nanoparticles in the clinic: An update," (in eng), *Bioeng Transl Med,* vol. 4, no. 3, p. e10143, Sep 2019, doi: 10.1002/btm2.10143.

[7] A. Y. Rwei, W. Wang, and D. S. Kohane, "Photoresponsive nanoparticles for drug delivery," (in eng), *Nano Today,* vol. 10, no. 4, pp. 451-467, Aug 1 2015, doi: 10.1016/j.nantod.2015.06.004.

[8] B. Fadeel *et al.*, "Advanced tools for the safety assessment of nanomaterials," (in eng), *Nat Nanotechnol,* vol. 13, no. 7, pp. 537-543, Jul 2018, doi: 10.1038/s41565-018-0185-0.

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ISSN (O) : 3093-4664

[9] M. M. Islam and S. Raikwar, "Enhancement of Oral Bioavailability of Protein and Peptide by Polysaccharide-based Nanoparticles," (in eng), *Protein Pept Lett,* vol. 31, no. 3, pp. 209-228, 2024, doi: 10.2174/0109298665292469240228064739.

[10] B. S. Pattni, V. V. Chupin, and V. P. Torchilin, "New Developments in Liposomal Drug Delivery," (in eng), *Chem Rev,* vol. 115, no. 19, pp. 10938-66, Oct 14 2015, doi: 10.1021/acs.chemrev.5b00046.

[11] H. K. Makadia and S. J. Siegel, "Poly Lactic-co-Glycolic Acid (PLGA) as Biodegradable Controlled Drug Delivery Carrier," (in eng), *Polymers (Basel),* vol. 3, no. 3, pp. 1377-1397, Sep 1 2011, doi: 10.3390/polym3031377.

[12] A. P. Dias *et al.*, "Dendrimers in the context of nanomedicine," *International Journal of Pharmaceutics,* vol. 573, p. 118814, 2020/01/05/ 2020, doi: https://doi.org/10.1016/j.ijpharm.2019.118814.

[13] E. C. Dreaden, A. M. Alkilany, X. Huang, C. J. Murphy, and M. A. El-Sayed, "The golden age: gold nanoparticles for biomedicine," (in eng), *Chem Soc Rev,* vol. 41, no. 7, pp. 2740-79, Apr 7 2012, doi: 10.1039/c1cs15237h.

[14] R. Li, Y. He, S. Zhang, J. Qin, and J. Wang, "Cell membrane-based nanoparticles: a new biomimetic platform for tumor diagnosis and treatment," *Acta Pharmaceutica Sinica B,* vol. 8, no. 1, pp. 14-22, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.apsb.2017.11.009.

[15] D. Schmaljohann, "Thermo- and pH-responsive polymers in drug delivery," (in eng), *Adv Drug Deliv Rev,* vol. 58, no. 15, pp. 1655-70, Dec 30 2006, doi: 10.1016/j.addr.2006.09.020.

[16] V. Gupta *et al.*, "Nanotechnology-driven cancer therapies for precision oncology: advances and clinical outlook," *International Journal of Nanomedicine,* pp. 1-33, 2026.

[17] X. Guo, Y. Cheng, X. Zhao, Y. Luo, J. Chen, and W. E. Yuan, "Advances in redox-responsive drug delivery systems of tumor microenvironment," (in eng), *J Nanobiotechnology,* vol. 16, no. 1, p. 74, Sep 22 2018, doi: 10.1186/s12951-018-0398-2.

[18] M. Mendes, J. J. Sousa, A. Pais, and C. Vitorino, "Targeted Theranostic Nanoparticles for Brain Tumor Treatment," (in eng), *Pharmaceutics,* vol. 10, no. 4, Oct 9 2018, doi: 10.3390/pharmaceutics10040181.

[19] H. Naderi-Meshkin, A. R. Bahrami, H. R. Bidkhori, M. Mirahmadi, and N. Ahmadiankia, "Strategies to improve homing of mesenchymal stem cells for greater efficacy in

ISSN (O) : 3093-4664

stem cell therapy," (in eng), *Cell Biol Int,* vol. 39, no. 1, pp. 23-34, Jan 2015, doi: 10.1002/cbin.10378.

[20] X. Yang, Y. Li, X. Liu, W. He, Q. Huang, and Q. Feng, "Nanoparticles and their effects on differentiation of mesenchymal stem cells," (in eng), *Biomater Transl,* vol. 1, no. 1, pp. 58-68, 2020, doi: 10.3877/cma.j.issn.2096-112X.2020.01.006.

[21] A. A. Aljabali *et al.*, "Nanomaterials and Their Impact on the Immune System," (in eng), *Int J Mol Sci,* vol. 24, no. 3, Jan 19 2023, doi: 10.3390/ijms24032008.

[22] W. L. Murphy, T. C. McDevitt, and A. J. Engler, "Materials as stem cell regulators," (in eng), *Nat Mater,* vol. 13, no. 6, pp. 547-57, Jun 2014, doi: 10.1038/nmat3937.

[23] S. Farjaminejad, R. Farjaminejad, and F. Garcia-Godoy, "Nanoparticles in Bone Regeneration: A Narrative Review of Current Advances and Future Directions in Tissue Engineering," (in eng), *J Funct Biomater,* vol. 15, no. 9, Aug 23 2024, doi: 10.3390/jfb15090241.

[24] M. Wang, G. Mi, D. Shi, N. Bassous, D. Hickey, and T. Webster, "Nanotechnology and Nanomaterials for Improving Neural Interfaces," *Advanced Functional Materials,* vol. 28, p. 1700905, 03/21 2018, doi: 10.1002/adfm.201700905.

[25] X. Cui *et al.*, "Bioderived Nanoparticles for Cardiac Repair," *ACS Nano,* vol. 18, no. 36, pp. 24622-24649, 2024/09/10 2024, doi: 10.1021/acsnano.3c07878.

[26] Y. Li, C. Xu, and C. Lei, "The Delivery and Activation of Growth Factors Using Nanomaterials for Bone Repair," (in eng), *Pharmaceutics,* vol. 15, no. 3, Mar 22 2023, doi: 10.3390/pharmaceutics15031017.

[27] K. A. Whitehead, R. Langer, and D. G. Anderson, "Knocking down barriers: advances in siRNA delivery," (in eng), *Nat Rev Drug Discov,* vol. 8, no. 2, pp. 129-38, Feb 2009, doi: 10.1038/nrd2742.

[28] J. M. Hare *et al.*, "Comparison of allogeneic vs autologous bone marrow–derived mesenchymal stem cells delivered by transendocardial injection in patients with ischemic cardiomyopathy: the POSEIDON randomized trial," (in eng), *Jama,* vol. 308, no. 22, pp. 2369-79, Dec 12 2012, doi: 10.1001/jama.2012.25321.

[29] C. L. Ventola, "Progress in Nanomedicine: Approved and Investigational Nanodrugs," (in eng), *P t,* vol. 42, no. 12, pp. 742-755, Dec 2017.

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