RESEARCH ARTICLE

BULLETIN OF SCIENTIFIC RESEARCH

Asian Research Association

DOI: 10.54392/bsr2422

Biomaterials for Regenerative Medicine and Revolutionizing Healthcare

K. Parvathy [1], M. Shanmugavadivu [1, *]

[1] Department of Biotechnology, Dr. N.G.P. Arts and Science College, Coimbatore, Tamil Nadu, India
*Corresponding author Email: shanmugavadivu@drngpasc.ac.in
DOI: https://doi.org/10.54392/bsr2422
Received: 09-07-2024; Revised: 22-10-2024; Revised: 03-11-2024; Published: 14-11-2024

Abstract: Biomaterials have become a key element in revolutionizing regenerative medicine, providing novel approaches to address a wide range of medical issues. Recent developments in biomaterials are tailored for conditions like osteoarthritis (OA), chronic wounds, erectile dysfunction (ED), and post-surgical tumor management. Composite hydrogels, such as GelMA/dECM, have shown promise in reducing chondrocyte pyroptosis and promoting osteochondral repair by recruiting mesenchymal stem cells. Additionally, the creation of MnO2 at CeOx-GAMP as a radiosensitizer demonstrates the potential of nanomaterials to activate the STING pathway, enhancing the effectiveness of radiotherapy. Functional hydrogels are being studied for skin wound healing applications, utilizing electric field stimulation and real-time healing monitoring through impedance mapping. Enzyme engineering, such as ChASE37, has proven effective in breaking down inhibitory proteoglycans in the central nervous system, aiding neuronal regeneration. The use of NIR-responsive hydrogels loaded with polydeoxyribonucleotides highlights innovative techniques for treating chronic wounds by enabling targeted drug delivery and promoting angiogenesis. For nerve injuries, magnetic mesoporous silica nanoparticles loaded with neurotrophic peptides have shown potential in restoring erectile function. Lastly, biomimetic nanofiber patches inspired by butterfly wings combine the advantages of tumor cell destruction and wound healing. These advancements exemplify the diverse applications of biomaterials, emphasizing their role in improving therapeutic efficacy and patient outcomes. As the field progresses, biomaterials hold the potential to dramatically transform healthcare and elevate the quality of life for millions worldwide.

Keywords: Biogenerate, Regenerative medicine, Osteoarthritis, Chronic Wounds, Nanomaterials, Tissue Regeneration

1. Introduction

Regenerative medicine provides a revolutionary approach to treating diseases and wounds by focusing on replacing or repairing damaged cells, tissues, and organs [1]. The underlying causes of illnesses such as acute trauma, degenerative diseases, and birth anomalies are often not addressed by conventional medical therapies. Conversely, regenerative medicine seeks to encourage regeneration by utilizing biomaterials or the body's natural healing processes [2].

Biomaterials—any materials made to interact with biological systems—are essential to the success of regenerative therapies. Among other things, these compounds can serve as structural support for tissue scaffolding, drug delivery systems, and mediators of cellular behavior [3]. Because it must possess specific properties such as mechanical strength, biocompatibility, biodegradability, and the ability to promote cellular interactions, choosing the appropriate biomaterial is crucial.

Recent developments in biomaterials science have led to the development of novel materials that closely resemble the original extracellular matrix (ECM). These substances enhance cell differentiation, adhesion, and proliferation. Natural biomaterials like collagen and chitosan give intrinsic bioactivity, whereas synthetic substitutes like polylactic acid (PLA) [4] and polycaprolactone (PCL) offer adjustable properties that can be adjusted for particular uses. Furthermore, new possibilities for tissue engineering and controlled drug delivery have been made possible by the use of smart materials, which respond to environmental stimuli [5].

2. Types of Biomaterials for Regenerative Medicine

Biomaterials play a vital role in regenerative medicine, with applications spanning stem cell therapy, drug delivery, and tissue engineering. In tissue engineering, biomaterials act as scaffolds that support the growth and organization of cells into functional tissues [6]. They enable the controlled and localized

release of therapeutic agents, enhancing treatment efficacy while minimizing side effects. Furthermore, biomaterials can influence stem cell differentiation, guiding them into specific cell types needed for tissue regeneration.

Despite the progress made, several challenges remain in the development of biomaterials for regenerative medicine, including concerns about long-term biocompatibility, scalability in production, and regulatory hurdles. Many advancements in regenerative medicine rely on biomaterials such as scaffolds, matrices, and delivery systems, which interact with biological tissues to support healing. Depending on their source, composition, and intended use, these materials can be categorized into various types. The selection of a particular biomaterial is largely determined by its intended application, whether for tissue engineering or drug delivery. Each type offers distinct benefits. The following section discusses the main categories of biomaterials used in regenerative medicine, recent breakthroughs that are reshaping healthcare, and an evaluation of their effectiveness.

2.1. Natural Biomaterials

Biological materials such as proteins, polysaccharides, and decellularized extracellular matrices (dECM) are used to create natural biomaterials that closely replicate the natural tissue environment. These materials are highly valued in regenerative medicine due to their inherent biocompatibility and bioactivity, making them ideal for applications like skin grafts, cartilage repair, and wound healing.

Collagen: Collagen hydrogels are used as scaffolds to support cell growth and differentiation, particularly in osteoarthritic joints [8]. These hydrogels are an attractive option for osteoarthritis (OA) treatment due to their biocompatibility and biodegradability, which help regenerate damaged cartilage by providing a conducive environment. Collagen hydrogels integrate into the injured cartilage, facilitating chondrocyte migration and the deposition of new extracellular matrix (ECM) components, thereby supporting tissue repair.

Hyaluronic acid (HA): Hyaluronic acid (HA), a natural polymer composed of β-glucuronic acid and N-acetyl-D-glucosamine, is a key glycosaminoglycan found in skin, connective tissues, and synovial fluid of joints [9-12].Due to its ability to retain water, along with its biocompatibility and biodegradability, HA has become an important biomaterial in regenerative medicine. It is utilized in a variety of applications, from promoting wound healing to serving as scaffolding in tissue engineering. HA-based hydrogels are being explored as scaffolds for healing peripheral nerve damage, offering potential solutions for functional recovery in neurodegenerative diseases.

2.2 Decellularized Extracellular Matrices (dECM)

Decellularized extracellular matrix (dECM) biomaterials are gaining increasing popularity in biomedical applications due to their ability to mimic the natural tissue environment. dECM is created by removing the cells from tissues, leaving behind a complex network of proteins, glycosaminoglycan's, and other components, as detailed by Qing Yao and colleagues (2019) [13]. This matrix serves as an effective scaffold for tissue engineering and regenerative medicine, supporting cell adhesion, growth, and differentiation. DECM-based materials are used in various applications, including drug delivery systems, wound healing, and organ regeneration. Their biocompatible and versatile nature helps promote tissue repair while minimizing immune responses.

2.3 Synthetic Biomaterials

Synthetic biomaterials are engineered in laboratories to precisely control their mechanical, chemical, and physical properties. These materials can be designed to degrade at specific rates, offering superior tunability compared to natural alternatives, depending on the therapeutic requirements. Biodegradable polymers like polylactic acid (PLA) and polyglycolic acid (PGA) are commonly used in applications such as drug delivery systems, tissue scaffolds, and surgical sutures [4]. PLA and PGA scaffolds have shown promise in the regeneration of bone and cartilage because they offer mechanical support while progressively breaking down as new tissue grows [14].

Drug transport and hydrogel production are only two of the many biomedical uses for polyethylene glycol (PEG), a flexible hydrophilic polymer. For example, PEG hydrogels are used as scaffolds for cell growth in tissue regeneration because of their low immunogenicity, simplicity of functionalization, and biocompatibility [15].

Conductive Polymers: In nerve and cardiac tissue engineering, conductive scaffolds that may electrically stimulate tissues are made from synthetic materials like polypyrrole (PPy) and poly (3, 4-ethylenedioxythiophene) (PEDOT) [16]. For bioelectronic applications, such as stimulating nerve regeneration with electricity, these materials provide the ability to interface with biological processes.

Although synthetic biomaterials are highly customizable and reproducible, they frequently lack the natural materials' innate bioactivity. This is being addressed by the development of hybrid biomaterials, which offer improved functioning and biocompatibility by combining the benefits of both natural and synthetic components [17].

2.4 Nanomaterials

Nanomaterials, which are characterized by their high surface area-to-volume ratio and nanoscale size, have transformed the field of regenerative medicine by interacting at the molecular level with biological systems. Their uses include tissue scaffolds, sensors, and medication delivery [18].

Nanoparticles: Therapeutic compounds have been delivered directly to injured tissues using metallic nanoparticles, such as gold and silver, which promote healing while reducing systemic side effects. For instance, magnetic mesoporous silica nanoparticles have demonstrated great potential in targeted therapy for erectile dysfunction and nerve regeneration [19].

Nanofibers: Polymers such as PLA or polycaprolactone (PCL) can be electrospun to create nanofibers that replicate the fibrous structure of natural tissues, which promotes cell adhesion and proliferation. Nanofiber scaffolds have shown exceptional efficacy in skin regeneration and wound healing [20].

Nanomaterials Based on Carbon: Graphene and carbon nanotubes have drawn interest due to their special electrical characteristics, which make them perfect for activating nerve tissue and developing bioelectronics for tissue regeneration and monitoring [21].

Although nanomaterials provide unmatched accuracy in producing materials with desired qualities for particular medicinal applications, further research is needed to determine their long-term safety and potential toxicity before being widely used in clinical settings.

2.5 Composite Biomaterials

To maximize the benefits of each component, composite biomaterials combine two or more distinct materials. These materials are extremely flexible in regenerative medicine because they are made to attain outstanding mechanical, chemical, and biological performance.

Hydrogel-Composites: Hydrogels combined with bioactive agents, growth factors, or nanoparticles have shown improved tissue engineering qualities. For example, decellularized extracellular matrix (dECM) and gelatin methacrylate (GelMA) combine to create a composite hydrogel that efficiently prevents chondrocyte pyroptosis and speeds up the healing of osteochondral defects [22].

Bioactive Glass Composites: Because bioactive glass can adhere to bone tissue and encourage cell proliferation, it is frequently utilized in dental implants [23] and bone regeneration when mixed with polymers or ceramic matrices to induce ontogenesis.

The future of regenerative medicine is closely linked to composite biomaterials, which provide versatile platforms that can be tailored to specific tissues and therapeutic goals. The variety of biomaterials used in this field, ranging from advanced nanocomposites to natural proteins, has significantly enhanced the potential for tissue regeneration and repair. While synthetic biomaterials provide strength and precision, natural biomaterials offer bioactivity and compatibility. Innovations such as nanomaterials and composites are poised to broaden the scope of regenerative medicine. Ongoing research focused on refining these biomaterials could lead to groundbreaking improvements in patient outcomes and the development of personalized treatments, revolutionizing healthcare.

3. Advances in Biomaterials for Osteoarthritis (OA) Treatment

3.1 Collagen GelMA/dECM Hydrogels for Osteochondral Repair

The Stimulator of Interferon Genes (STING) pathway plays a crucial role in activating the body's innate immune response to tumors. This process is triggered when cytosolic double-stranded DNA (dsDNA), often released due to cellular damage such as that caused by radiation therapy, is detected. Upon recognizing dsDNA, cyclic GMP-AMP synthase (cGAS) produces the second messenger 2', 3'-cyclic GMP-AMP (cGAMP). This molecule then binds to STING, initiating a signaling cascade that leads to the production of pro-inflammatory cytokines and type I interferons. These signaling molecules enhance the immune system's ability to recognize and destroy tumor cells by promoting dendritic cell maturation and activating cytotoxic T-cells.

Using MnO_2 Nanomaterials to Improve Radiotherapy: Nanomaterials based on MnO_2 have been developed to improve radiotherapy efficacy in a number of ways. Reactive oxygen species (ROS) are the main way that MnO_2 nanoparticles raise oxidative stress in the tumor microenvironment. MnO_2 functions as a catalyst when exposed to X-rays, transforming superoxide anions into hydrogen peroxide (H_2O_2), which is then converted by Fenton-like processes into extremely hazardous hydroxyl radicals (·OH). By causing significant DNA damage inside cancer cells, these radicals encourage the release of dsDNA into the cytoplasm, which in turn triggers the cGAS-STING pathway (Nanomaterials).

MnO_2 nanoparticles not only generate ROS but also catalyze the breakdown of H_2O_2, which improves the oxygenation of the tumor tissue and

alleviates tumor hypoxia. MnO_2 is a powerful radiosensitizer because of its dual action of increased oxidative stress and better oxygenation. Additionally, these nanomaterials exhibit glutathione oxidase (GSHOx) ---like activity, which lowers glutathione levels in tumors and inhibits ROS neutralization, increasing the effectiveness of radiation therapy (Nanomaterials).

Current Research on MnO_2 in Radiotherapy at CeOx-GAMP: Recent research has shown that MnO_2, cerium oxide (CeOx), and cyclic GMP-AMP (cGAMP) work in concert to improve the results of radiation therapy. Because of their oxygen vacancy-rich architectures, CeOx nanoparticles have enzyme activity similar to those of superoxide dismutase (SOD) and peroxidase (POD), which aid in the breakdown of superoxide into $H2O_2$ and the subsequent generation of ROS. By supplying exogenous cGAMP, which when combined with the dsDNA secreted from tumor cells, improves immune activation, the addition of cGAMP to MnO_2@CeOx-GAMP (MCG) nanoparticles amplifies STING pathway activation (Nanomaterials).

Research has indicated that MnO_2@CeOx-GAMP nanoparticles enhance the radiation sensitivity of cancer cells, leading to more robust anti-tumor immune responses. Increases in survival rates in cancer model animals indicate that these nanomaterials improve tumor treatment and reduce radio-resistance by increasing reactive oxygen species (ROS) production and activating the STING pathway. [24-27].

4. Functional Hydrogels in Skin Wound Healing

4.1 Electric Field Stimulation and Impedance Mapping

Hydrogels combined with electric field stimulation (EFS) have proven to be an effective approach for enhancing skin wound healing. EFS can influence key biological processes, including cell migration, proliferation, and differentiation [28]. Specifically, low-frequency electric fields promote the directional movement of endothelial cells, fibroblasts, and keratinocytes toward the wound site, accelerating healing by stimulating angiogenesis and tissue repair. Additionally, EFS can trigger the release of essential growth factors, such as transforming growth factor-beta (TGF-β) and vascular endothelial growth factor (VEGF), which are vital for tissue regeneration.

In this process, hydrogels—particularly conductive hydrogels—play a crucial role by acting as a conduit for the direct delivery of electrical stimulation to the wound. These hydrogels make it easier to apply electric fields while preserving tissue compatibility because they are frequently integrated with conductive elements like PEDOT. Their innate ionic conductivity maximizes cell reactivity to the electric fields by simulating the normal tissue environment. Hydrogels not only aid in the healing process but also offer real-time monitoring through impedance mapping. The hydrogel's impedance drops as the wound heals and the tissue grows back, offering a non-invasive way to gauge wound closure and the healing process (Hydrogel) [29].

4.2 NIR-responsive Hydrogels for Chronic Wound Healing

In the treatment of chronic wounds, near-infrared (NIR)--responsive hydrogels are a major breakthrough, especially when it comes to medication delivery, angiogenesis promotion, and tissue regeneration acceleration. These hydrogels contain photothermal agents, namely molybdenum disulfide nanosheets (MoS_2 NSs), which produce localized heat by absorbing near-infrared light. Cell proliferation and angiogenesis, two biological processes essential for wound healing, are improved by this mild hyperthermia (Hydrogel). These hydrogels are exceptionally successful at delivering drugs to chronic wounds because their heat response also causes the release of therapeutic substances.

In diabetic wounds, where healing is delayed and inflammation is high, NIR-responsive hydrogels containing therapeutic compounds can be particularly helpful. In a diabetic wound model, for instance, a NIR-responsive hydrogel with polydeoxyribonucleotide (PDRN) nano-vectors has demonstrated efficacy. The hydrogel released PDRN when exposed to NIR radiation, which decreased inflammation and encouraged the production of collagen and angiogenesis. In diabetic mice, this resulted in a notable acceleration in wound healing (Hydrogel electric) [30].

For chronic wound situations, where regulated, on-demand drug administration is essential, NIR-responsive hydrogels can be customized. These hydrogels can release therapeutic chemicals at certain intervals by varying the length and intensity of NIR exposure, which makes it easier to treat the wound continuously (Hydrogel electric).

5. Engineered Enzymes for Central Nervous System Repair

5.1 Chondroitinase ABC (ChASE37) for CNS Regeneration

Injuries to the central nervous system (CNS), such as spinal cord damage or neurodegenerative disorders, often result in the formation of inhibitory scar tissue made up mainly of chondroitin sulfate proteoglycans (CSPGs) [31, 32], found in the

extracellular matrix (ECM), play a key role in limiting neuronal regrowth. CSPGs act as both physical and metabolic barriers, significantly hindering the natural healing process after CNS injuries by preventing axonal regeneration and repair [36].

5.1.1. Structure and Function of Chondroitin Sulfate Proteoglycans (CSPGs)

Chondroitin sulfate proteoglycans (CSPGs) are complex molecules composed of a core protein linked to chains of chondroitin sulfate glycosaminoglycans (GAGs). These molecules play an essential role in scar tissue formation following central nervous system (CNS) injury by inhibiting axonal growth. CSPGs interact with several neuronal receptors, such as leukocyte common antigen-related phosphatase (LAR) and receptor protein-tyrosine phosphatase σ (RPTPσ), which regulate key processes like axonal growth and dendritic spine formation [33].

Following CNS injury, reactive astrocytes secrete large quantities of CSPGs, forming a dense extracellular barrier that limits plasticity, stabilizes synapses, and prevents regenerated axons from reconnecting. While CSPGs are important for the immediate stabilization of the injury site, they hinder recovery during the sub-acute and chronic phases. As a result, they pose a significant obstacle to long-term nerve repair [34, 36].

5.1.2. ChASE37: Degrading CSPGs to Promote Neural Regeneration

Chondroitinase ABC (ChASE) promotes axonal regeneration by cleaving the glycosaminoglycan chains of chondroitin sulfate proteoglycans (CSPGs), effectively removing inhibitory barriers. A more stable variant, ChASE37, has been developed through mutations and computational modeling, showing enhanced stability and bioactivity compared to the native enzyme. This modified enzyme helps facilitate axonal growth, cell adhesion, and neural repair by breaking down CSPGs in the extracellular matrix [35].

ChASE37, which features 37 point mutations, is more resistant to proteolytic degradation and exhibits greater thermal stability than its native counterpart. This makes it better suited for long-term treatments of CNS injuries, as it retains a higher percentage of its activity over time. By degrading CSPGs, ChASE37 supports axonal regeneration and synaptic plasticity, which are crucial for restoring neurological function following injury.

5.2. Preclinical Data and Outcomes

Preclinical studies have demonstrated that ChASE37 is effective in promoting neuronal repair in rodent models of central nervous system (CNS) injuries, such as stroke and spinal cord damage. In these models, ChASE37 treatment significantly reduced the presence of chondroitin sulfate proteoglycans (CSPGs) at the injury site, which in turn enhanced axonal sprouting. For example, in mouse stroke models, ChASE37 was delivered to the injury site using an affinity-based hydrogel, allowing for targeted and prolonged release. This resulted in higher expression levels of axonal growth markers like GAP-43, which plays a crucial role in tissue plasticity and axonal regeneration.

In spinal cord injury studies, animals treated with ChASE37 exhibited notable improvements in motor function recovery compared to control groups. These findings emphasize ChASE37's therapeutic potential in CNS regeneration, particularly its ability to break down inhibitory CSPGs and stimulate the nervous system's natural repair mechanisms.

In conclusion, ChASE37 represents a promising advancement in CNS regenerative medicine. It offers a novel approach to overcoming the inhibitory effects of CSPGs, supporting neuron repair, and promoting the reconnection of disrupted neural pathways after CNS trauma [36].

6. Nanoparticles for Nerve Regeneration and Erectile Dysfunction (ED)

6.1 Magnetic Mesoporous Silica Nanoparticles for Erectile Dysfunction

Erectile dysfunction (ED) is often caused by damage to the cavernous nerves, which are critical for maintaining erectile function. Neurogenic ED can result from cavernous nerve injury (CNI), which may occur due to pelvic trauma or surgeries like radical prostatectomy. Traditional treatments, such as phosphodiesterase type 5 inhibitors (PDE5is), are limited in their effectiveness for ED caused by nerve damage because they primarily target vascular components and rely on intact neural pathways [37]. This highlights the need for innovative therapies focused on nerve regeneration for patients with CNI-induced ED.

Magnetic mesoporous silica nanoparticles (MSNs) have shown potential in addressing this issue. These nanoparticles, loaded with neurotrophic peptides, offer targeted nerve regeneration and repair. Thanks to their magnetic properties, Fe3O4-coated MSNs can be precisely directed to the injury site using an external magnetic field. Once at the site, the mesoporous structure enables controlled drug release and promotes nerve repair by creating a favorable environment for neurotrophic activity.

6.2. Causes of Nerve Injury-Induced ED and Treatment Limitations

Nerve injury-induced erectile dysfunction (ED) occurs when signals from the brain and spinal cord fail to effectively reach the corpora cavernosa, preventing adequate blood flow and erection. This type of ED can be caused by spinal cord injuries, neurological disorders such as multiple sclerosis or Parkinson's disease, and surgeries like prostatectomy. Current treatments, such as PDE5 inhibitors, are often ineffective for patients with significant nerve damage, as they primarily work in cases with minimal nerve injury. Therefore, new treatment strategies are essential, as patients with severe nerve impairment often do not respond well to existing therapies.

Magnetic mesoporous silica nanoparticles, particularly those coated with Fe3O4, present several advantages for nerve regeneration. When guided to the injury site by an external magnetic field, these nanoparticles help concentrate therapeutic agents at the affected area, accelerating the healing process of damaged nerves. Neurotrophic peptides like RADA16-I and RAD-RGI, loaded within the mesopores, encourage axonal growth and the repair of the myelin sheath, aiding in the restoration of nerve function. This targeted approach minimizes the risk of damaging surrounding healthy tissues by delivering localized treatment [38, 39].

The unique structure of these nanoparticles ensures a controlled and sustained release of neurotrophic peptides, providing a prolonged therapeutic effect. Magnetic mesoporous silica nanoparticles (MMSNs) have demonstrated excellent biocompatibility and low cytotoxicity, making them suitable for use in living organisms. Their superparamagnetic properties not only support magnetic targeting but also offer potential for other therapeutic applications, such as hyperthermia, when exposed to alternating magnetic fields [40]. To help restore erectile function in patients with cavernous nerve injury (CNI)-induced erectile dysfunction, the peptides promote neuronal adhesion, axon growth, and overall nerve regeneration.

6.3. Preclinical and Clinical Data

Preclinical studies have demonstrated that magnetic mesoporous silica nanoparticles (MSNs) are effective in restoring erectile function in rat models with bilateral cavernous nerve injury (BCNI). Rats treated with peptide-loaded MSNs showed significant improvements in erectile function and nerve regeneration compared to control groups. The treated groups exhibited notably higher maximum intracavernous pressure (ICP) to mean arterial pressure (MAP) ratios, indicating better erectile performance. Histological analysis also revealed nerve tissue regeneration, showing increased smooth muscle content and reduced fibrosis in the corpus cavernosum [41-43].

These promising preclinical results suggest that magnetic mesoporous silica nanoparticles could revolutionize the treatment of erectile dysfunction (ED) caused by nerve damage. By offering a targeted and efficient approach that enhances nerve repair and restores function, this method holds significant therapeutic potential for patients experiencing ED following surgeries like radical prostatectomy [19].

7. Biomimicry in Tumor Treatment: Butterfly-Wing-Inspired Nanofiber Patches

Biomimicry, the process of designing materials that mimic biological structures and functions, has sparked innovative advancements in medical technology. One of the most fascinating applications of biomimicry in cancer treatment is the development of nanofiber patches that resemble butterfly wings. These patches are specifically designed to address two critical postoperative needs: enhancing wound healing and targeting any residual tumor cells [44].

7.1. Butterfly-Wing-Inspired Design and Its Application in Nanofiber Patches

The design of nanofiber patches with complex hierarchical structures is inspired by the intricate arrangement of butterfly wings, which consist of stacked scales. Butterfly wings are ideal for bioengineering due to their large surface area and ability to absorb light efficiently. Techniques such as electrospinning and electrostatic spraying are employed to replicate this structural complexity in the nanofiber patches. The use of natural materials like polylactic acid (PLA), black rice powder (BRP), and konjac glucomannan (KGM) enhances the biocompatibility and biodegradability of these patches [45].

WingPatch, a nanofiber patch modeled after butterfly wings, features a multilayered, porous structure. This design not only facilitates efficient photothermal conversion but also provides a platform for the sustained release of therapeutic agents, such as paclitaxel (PTX). The patch's porous nature promotes tissue regeneration, and its ability to absorb light and convert it into heat helps with the localized destruction of tumors [46].

7.2. Dual Function: Tumor Cell Elimination and Wound Healing

One of the main advantages of these nanofiber patches is their dual functionality. Tumor recurrence can occur when cancer cells are left behind during

treatment, particularly after procedures where complete eradication is challenging. The WingPatch addresses this issue through photothermal therapy (PTT). When exposed to near-infrared light, the patch heats up, inducing localized hyperthermia that targets and destroys any remaining tumor cells in the surgical area. The addition of BRP enhances this effect by improving photothermal conversion and providing antibacterial properties to prevent infections after surgery [45].

Simultaneously, the biomimetic design of the patch promotes wound healing. Inspired by the extracellular matrix, the nanofibers encourage cell adhesion, migration, and proliferation—critical processes for tissue regeneration. KGM, an essential component of the patch, plays a key role in accelerating tissue recovery and maintaining the structural integrity of the patch as it heals. This ensures that surrounding tissue repairs effectively while tumor cells are being eliminated [45].

7.3. Innovations and Potential Applications in Oncology and Regenerative Medicine

Recent advancements in biomimetic nanofiber technology have shown promising results in both preclinical and clinical settings. For an instance, the WingPatch has demonstrated significant potential in animal models, enhancing the effectiveness of treatments for liver and breast cancer. In addition to serving as a barrier against infections, these patches have promoted tissue regeneration and improved wound healing in mice, while also reducing the likelihood of tumor recurrence.

Nanofiber patches designed to resemble butterfly wings have numerous potential applications in oncology moving forward. These patches could be particularly useful in postoperative care for various cancers, where successful recovery depends on both tissue regeneration and the removal of tumors. Furthermore, the adaptable nanofiber structure can be customized to accommodate different cancer types and patient-specific needs [47], allowing for the integration of multiple therapeutic agents. Beyond oncology, these biomimetic patches could also be applied in regenerative medicine for conditions like chronic wounds or tissue engineering, where enhanced tissue repair is needed [48].

In conclusion, butterfly wing-shaped nanofiber patches represent a groundbreaking innovation in regenerative medicine and cancer treatment. By combining biomimicry with cutting-edge nanotechnology, these patches offer a dual approach to eradicating cancer cells while facilitating wound healing, positioning them as a crucial tool in the future of healthcare.

8. Conclusion

Biomaterials have emerged as a key contributor to advancements in regenerative medicine, offering innovative solutions to a wide range of medical challenges. These materials have shown great promise in transforming healthcare, from addressing degenerative diseases like osteoarthritis to enhancing cancer therapies and supporting tissue regeneration.

The recent advancements in biomaterial development have significantly influenced various medical fields. The use of biomimetic materials, synthetic enzymes, functional hydrogels, composite hydrogels, and nanomaterials has proven beneficial in improving patient outcomes and boosting the effectiveness of treatments.

Together, these innovations highlight the vast potential of biomaterials to provide cutting-edge solutions in disease treatment, drug delivery, tissue regeneration, and patient care across different medical sectors. As the field continues to evolve, biomaterials hold the potential to revolutionize healthcare and improve millions of lives. Future research should focus on expanding the role of biomaterials in personalized medicine and exploring their ability to address unmet medical needs.

References

[1] A.S. Mao, D.J. Mooney, Regenerative medicine: Current therapies and future directions. Proceedings of the National Academy of Sciences of the United States of America, 112(47), (2015) 14452–14459. [DOI]

[2] Jaklenec, A. Stamp, E. Deweerd, A. Sherwin, R. Langer, Progress in the tissue engineering and stem cell industry “are we there yet?. Tissue Engineering Part B: Reviews, 18(3) (2012)155–166. [DOI]

[3] Yang, N.T. Blum, J. Lin, J. Qu, P. Huang, Biomaterial scaffold-based local drug delivery systems for cancer immunotherapy. Science Bulletin, 65(17), (2020) 1489-1504. [DOI]

[4] S. Castañeda-Rodríguez, M. González-Torres, R.M. Ribas-Aparicio, M.L. Del Prado-Audelo, G. Leyva-Gómez, E.S. Gürer, J. Sharifi-Rad, Recent advances in modified poly (lactic acid) as tissue engineering materials. Journal of biological engineering, 17(1), (2023) 21. [DOI]

[5] B. Cecen, S. Hassan, X. Li, Y.S. Zhang, Smart Biomaterials in Biomedical Applications: Current Advances and Possible Future Directions. Macromolecular bioscience, 24(3), (2024) e2200550. [DOI]

[6] E.J. Lee, F.K. Kasper, A.G. Mikos, Biomaterials for tissue engineering. Annals of biomedical engineering, 42(2), (2014) 323–337. [DOI]

[7] R. Geevarghese, S.S. Sajjadi, A. Hudecki, S. Sajjadi, N.R. Jalal, T. Madrakian, M. Ahmadi, M.K.W. Biegun, S. Ghavami, W. Likus, K. Siemianowicz, M.J. Łos, Biodegradable and non-biodegradable biomaterials and their effect on cell differentiation. International Journal of Molecular Sciences, 23(24), (2022) 16185.[DOI]

[8] M. Zhang, W. Hu, C. Cai, Y. Wu, J. Li, S. Dong, Advanced application of stimuli-responsive drug delivery system for inflammatory arthritis treatment. Materials Today Bio, 14, (2022) 100223. [DOI]

[9] K. Valachová, M.E. Hassan, L. Soltés, Hyaluronan: Sources, Structure, Features and Applications. Molecules, 29(3), (2024) 739. [DOI]

[10] Y.H. Liao, S.A. Jones, B. Forbes, G.P. Martin, M.B. Brown, Hyaluronan: pharmaceutical characterization and drug delivery. Drug delivery, 12(6), (2005) 327-342. [DOI]

[11] T. Kobayashi, T. Chanmee, N. Itano, Hyaluronan: Metabolism and Function. Biomolecules, 10, (2020)1525. [DOI]

[12] H. Yang, L. Song, Y. Zou, D. Sun, L. Wang, Z. Yu, J. Guo, Role of Hyaluronic Acids and Potential as Regenerative Biomaterials in Wound Healing. ACS Applied Bio Materials, 4, (2021) 311–324. [DOI]

[13] Q. Yao, Y.W. Zheng, Q.H. Lan, L. Kou, H.L. Xu, Y.Z. Zhao, Recent development and biomedical applications of decellularized extracellular matrix biomaterials. Materials Science and Engineering: C, 104, (2019) 109942. [DOI]

[14] M. Wang, Z. Yuan, N. Ma, C. Hao, W. Guo, G. Zou, Y. Zhang, M. Chen, S. Gao, J. Peng, A. Wang, Y. Wang, X. Sui, W. Xu, S. Lu, S. Liu, Q. Guo, Advances and Prospects in Stem Cells for Cartilage Regeneration. Stem Cells International, 2017, (2017) 4130607. [DOI]

[15] S. Sun, Y. Cui, B. Yuan, M. Dou, G. Wang, H. Xu, J. Wang, W. Yin, D. Wu, C. Peng, Drug delivery systems based on polyethylene glycol hydrogels for enhanced bone regeneration. Frontiers in bioengineering and biotechnology, 11, (2023) 1117647. [DOI]

[16] R. Balint, N.J. Cassidy, S.H. Cartmell, Conductive polymers: Towards a smart biomaterial for tissue engineering. Acta biomaterialia, 10(6), (2014) 2341-2353. [DOI]

[17] G. Satchanska, S. Davidova, P.D. Petrov, Natural and Synthetic Polymers for Biomedical and Environmental Applications. Polymers, 16(8), (2024) 1159. [DOI]

[18] Hasan, M. Morshed, A. Memic, S. Hassan, T.J. Webster, H.E. Marei, Nanoparticles in tissue engineering: applications, challenges, and prospects. International journal of nanomedicine, 13, (2018) 5637–5655. [DOI]

[19] X. Liang, Z. Wang, S. Wang, F. Ruan, Y. Zhang, D. Shao, X. Liu, F. Chen, X. Shi, Magnetic mesoporous silica nanoparticles loaded with peptides for the targeted repair of cavernous nerve injury underlying erectile dysfunction. Biomaterials, 314, (2025) 122811. [DOI]

[20] N. Palani, P. Vijayakumar, P. Monisha, S. Ayyadurai, S. Rajadesingu, Electrospun nanofibers synthesized from polymers incorporated with bioactive compounds for wound healing. Journal of Nanobiotechnology, 22(1), (2024) 211. [DOI]

[21] R. Vasita, D.S. Katti, Nanofibers and their applications in tissue engineering. International journal of nanomedicine, 1(1), (2006) 15–30. [DOI]

[22] D. Convertino, M.L. Trincavelli, C. Giacomelli, L. Marchetti, C. Coletti, Graphene-based nanomaterials for peripheral nerve regeneration. Frontiers in Bioengineering and Biotechnology, 11, (2023) 1306184. [DOI]

[23] J. Meng, J. Lu, C. Jiang, L. Deng, M. Xiao, J. Feng, T. Ren, Q. Qin, S. Guo, H. Wang, J. Yao, J. Li, Collagen hydrogel-driven pyroptosis suppression and combined microfracture technique delay osteoarthritis progression. Biomaterials, 314, (2025) 122817. [DOI]

[24] A.C. Profeta, G.M. Prucher, Bioactive-glass in periodontal surgery and implant dentistry. Dental Materials Journal, 34(5), (2015) 559–571. [DOI]

[25] W. Dong, M. Chen, C. Chang, T. Jiang, L. Su, C. Chen, G. Zhang, Remodeling of Tumor Microenvironment by Nanozyme Combined cGAS–STING Signaling Pathway Agonist for Enhancing Cancer Immunotherapy. International Journal of Molecular Sciences, 24, (2023) 13935. [DOI]

[26] T. Zhang, C. Hu, W. Zhang, Y. Ruan, Y. Ma, D. Chen, Y. Huang, S. Fan, W. Lin, Y. Huang, K. Liao, H. Lu, J. Xu, J. Pi, X. Guo, Advances of MnO_2 nanomaterials as novel agonists for the development of cGAS-STING-mediated therapeutics. Frontiers in Immunology, 14, (2023) 1156239. [DOI]

[27] C. Yang, Y. Liang, N. Liu, M. Sun, Role of the cGAS-STING pathway in radiotherapy for non-small cell lung cancer. Radiation Oncology, 18, (2023) 145. [DOI]

[28] M. Tan, Z. Gao, X. Wang, X. Wang, C. Lin, Y. Huang, W. Chen, Y. Zhang, Z. Hou, MnO2@ CeOx-GAMP radiosensitizer with oxygen vacancies depended mimicking enzyme-like activities for radiosensitization-mediated STING pathway activation. Biomaterials, 314, (2025) 122797. [DOI]

[29] L.C. Kloth, Electrical stimulation technologies for wound healing. Advances in wound care, 3(2), (2014) 81-90. [DOI]

[30] Y. Shin, H.S. Lee, J.U. Kim, Y.H. An, Y.S. Kim, N.S. Hwang, D.H. Kim, Functional-hydrogel-based electronic-skin patch for accelerated healing and monitoring of skin wounds. Biomaterials, 314, (2025) 122802. [DOI]

[31] Y. Sun, Y. Li, X. Ding, P. Xu, X. Jing, H. Cong, H. Hu, B. Yu, F.J. Xu, An NIR-responsive hydrogel loaded with polydeoxyribonucleotide nano-vectors for enhanced chronic wound healing. Biomaterials, 314, (2025) 122789. [DOI]

[32] Rolls, R. Shechter, M. Schwartz, The bright side of the glial scar in CNS repair. Nature Reviews Neuroscience, 10(3), (2009) 235-241. [DOI]

[33] .P. Tran, P.M. Warren, J. Silver, The biology of regeneration failure and success after spinal cord injury. Physiological reviews, 98(2), (2018) 881-917. [DOI]

[34] S. Avram, S. Shaposhnikov, C. Buiu, M. Mernea, Chondroitin sulfate proteoglycans: structure-function relationship with implication in neural development and brain disorders. BioMed research international, 2014, (2014) 642798. [DOI]

[35] R. Yang, Y. Zhang, J. Kang, C. Zhang, B. Ning, Chondroitin Sulfate Proteoglycans Revisited: its Mechanism of Generation and Action for Spinal Cord Injury. Aging and disease, 15(1), (2024)153–168. [DOI]

[36] J. Hu, L.Q. Jin, M.E. Selzer, Inhibition of central axon regeneration: perspective from chondroitin sulfate proteoglycans in lamprey spinal cord injury. Neural regeneration research, 17(9), (2022) 1955–1956. [DOI]

[37] N.L. Khait, S. Zuccaro, D. Abdo, H. Cui, R. Siu, E. Ho, C.M. Morshead, M.S. Shoichet, Redesigned chondroitinase ABC degrades inhibitory chondroitin sulfate proteoglycans in vitro and in vivo in the stroke-injured rat brain. Biomaterials, 314, (2025) 122818. [DOI]

[38] G. Corona, D.M. Lee, G. Forti, D.B. O'Connor, M. Maggi, N. Pendleton, G. Bartfai, S. Boonen, F.F. Casanueva, J.D. Finn, A. Giwercman, T.S. Han, I.T. Huhtaniemi, K. Kula, M.E.J. Lean, M. Punab, A.J. Silman, D. Vanderschueren, F.C.W. Wu, T.W. O'Neill, EMAS Study Group. Age-related changes in general and sexual health in middle-aged and older men: results from the European Male Ageing Study (EMAS). The journal of sexual medicine, 7(4), (2010) 1362-1380. [DOI]

[39] B.S. Sivamaruthi, D.U. Kapoor, R.R. Kukkar, M. Gaur, G.M. Elossaily, B.G. Prajapati, C. Chaiyasut, Mesoporous Silica Nanoparticles: Types, Synthesis, Role in the Treatment of Alzheimer's Disease, and Other Applications. Pharmaceutics, 15 (2023) 2666. [DOI]

[40] E. Rascol, M. Daurat, A. Da Silva, M. Maynadier, C. Dorandeu, C. Charnay, M. Garcia, J. Lai-Kee-Him, P. Bron, M. Auffan, W. Liu, B. Angeletti, J.M. Devoisselle, Y. Guari, M.Gary-Bobo, Biological Fate of Fe3O4 Core-Shell Mesoporous Silica Nanoparticles Depending on Particle Surface Chemistry. Nanomaterials, 7, (2017) 162. [DOI]

[41] C. Tao, Y. Zhu, Magnetic mesoporous silica nanoparticles for potential delivery of chemotherapeutic drugs and hyperthermia. Dalton transactions (Cambridge, England : 2003), 43(41), (2014) 15482–15490. [DOI]

[42] X. Ma, W. Yang, P. Nie, Z. Zhang, Z. Chen, H. Wei, Implantation of skin-derived precursor Schwann cells improves erectile function in a bilateral cavernous nerve injury rat model. Basic and clinical andrology, 33(1), (2023) 11. [DOI]

[43] J.Q. Zhu, H.K. Lu, Z.Q. Cui, Y.C. Wang, Y.H. Li, W. Zhao, Q. Fu, Y.M. Xu, Y. Xu L.J. Song, Therapeutic potential of human umbilical cord blood mesenchymal stem cells on erectile function in rats with cavernous nerve injury. Biotechnology Letters, 37, (2015) 1515-1525. [DOI]

[44] H. Zheng, K. Chen, Y. Dun, Y. Xu, A. Zhou, H. Ge, Y. Yang, X. Ning, Harnessing Nature's Ingenuity to Engineer Butterfly-Wing-Inspired Photoactive Nanofiber Patches for Advanced Postoperative Tumor Treatment. Biomaterials, 314, (2025) 122808. [DOI]

[45] P.P. Chen, H.P. Zhang, J. Ding, X.Y. Lin, X. Lu, C.S. Liu, Y. Tang, Carboxymethyl Konjac Glucomannan Conjugated Polydopamine Composites for Pb(II) Removal. Carbohydrate Polymers, 162, (2017) 62-70. [DOI]

[46] J. Hu, D. Kai, H. Ye, L. Tian, X. Ding, S. Ramakrishna, X.J. Loh, Electrospinning of Poly(Glycerol Sebacate)-Based Nanofibers for Nerve Tissue Engineering. Materials Science and Engineering C, 70(2-1), (2017) 1089–1094. [DOI]

[47] P. Tipduangta, P. Belton, L. Fabian, L.Y. Wang, H. Tang, M.D. Eddleston, S. Qi, Electrospun Polymer Blend Nanofibers for Tuneable Drug Delivery: The Role of Transformative Phase Separation. Molecular Pharmaceutics, 13(1), (2016) 25–39. [DOI]

[48] K.T. Noh, H.Y. Lee, U.S. Shin, H.W. Kim, Composite Nanofiber of Bioactive Glass Nanofiller Incorporated Poly (Lactic Acid) for Bone Regeneration. Materials Letters, 64(7), (2010) 802–805. [DOI]

Funding

No funding was received for the conduct of this research

Conflict of interest

The authors declare that no conflict of interest exists.

Does the Article Screened for Similarity?

Yes.

About the License