Nanotechnology and Biomaterials in Orthopaedic Medical Applications

Yihan Sun *

Material science and engineering in Queen Mary University of London Engineering School, Northwestern Polytechnical University, Xi' an, China

* Corresponding Author Email: jp2021304049@qmul.ac.uk

Abstract. The convergence of nanotechnology and biomaterials has heralded a transformative era in orthopaedics, revolutionizing the diagnosis, treatment, and rehabilitation of musculoskeletal disorders. This paper explores the profound impact of this synergy, focusing on innovations in implant design, regenerative therapies, targeted drug delivery, and advanced diagnostics. Nanotechnology's precision engineering has enabled the creation of implants that mimic natural bone, facilitating integration and improving mechanical stability. The fusion with biomaterials has led to scaffolds that foster tissue regeneration and implants with enhanced biocompatibility and longevity. The paper also delves into the challenges of this convergence, such as ensuring biocompatibility, navigating regulatory landscapes, and translating laboratory innovations into clinical practice. The research found that the strategic integration of nanotechnology and biomaterials holds immense promise for reshaping orthopaedic care, enhancing patient outcomes, and elevating the standards of treatment. This research signifies a critical exploration of the convergence of nanotechnology and biomaterials within orthopaedics, offering a comprehensive analysis that not only elucidates the transformative potential of this fusion but also provides insights and guidance for future research and clinical applications, thereby contributing to the advancement of personalized and effective treatments in the field.

Keywords: Nanotechnology; Biomaterials; Orthopaedics; Implant design; Regenerative therapies.

1. Introduction

The convergence of nanotechnology and biomaterials has brought about a paradigm shift in the field of orthopaedics, revolutionizing how musculoskeletal disorders are diagnosed, treated, and rehabilitated. These cutting-edge technologies have not only enhanced patient prognoses but have also significantly improved their quality of life. This discourse delves into the profound impact of nanotechnology and biomaterials in reshaping the landscape of orthopaedic care.

Nanotechnology has introduced groundbreaking possibilities in orthopaedics. As a vanguard of innovation, nanotechnology has instigated transformative changes: Orthopaedic implants, including bone screws and joint replacements, have reaped substantial benefits from nanotechnology. By designing implants at the nanoscale, scientists and engineers can replicate the intricate architecture of natural bone, leading to better integration with surrounding tissues and reduced rejection rates while simultaneously enhancing mechanical stability. Furthermore, nanotechnology enables the crafting of implants and prosthetics tailored to the unique anatomies of individuals such as dental aspects [1]. Leveraging advanced imaging techniques and 3D printing, orthopaedic surgeons can now achieve an unparalleled fit, function, and comfort for each patient. The precision offered by nanotechnology has also brought about a revolution in orthopaedic drug delivery. Engineered nanoparticles can effectively transport therapeutic agents, releasing them specifically at targeted sites in the body. This targeted approach is particularly valuable in addressing conditions like arthritis, osteoporosis, and tissue inflammation. In addition, nanoscale imaging technologies have enriched the diagnostic capabilities of orthopaedics, providing intricate insights into the bone structure, mineralization, and cellular interactions, thereby enabling early and accurate disease detection.

Biomaterials, designed to seamlessly interact with biological systems, have made substantial contributions to orthopaedic care across various contexts: Biomaterial scaffolds play a crucial role in providing a supportive framework for cellular regeneration in damaged bone and cartilage [2]. The synergy of biomaterials with nanotechnology has yielded scaffolds that closely mimic native tissues, fostering more efficacious tissue regeneration. Moreover, biomaterials have the potential to mitigate the risk of infections associated with orthopaedic implants by incorporating nanoscale antimicrobial agents, thus addressing a critical aspect of post-operative complications. Biomaterials, particularly when in conjunction with nanotechnology, offer insights into the biomechanics of bones and joints at the nanoscale. This comprehension aids in the development of precise models that predict the behavior of implants and tissues under diverse conditions.

The fusion of nanotechnology and biomaterials has ushered in a new era for orthopaedic care, revolutionizing implant design, drug delivery, diagnostics, and tissue regeneration. This synergy between advanced technologies and medical science holds immense promise for enhancing patient well-being and redefining the standards of orthopaedic treatment. Herein, this paper introduces the profound impact of nanotechnology and biomaterials on reshaping orthopaedic medical applications. It summarizes how the convergence of these technologies has revolutionized implant design, drug delivery, diagnostics, and tissue regeneration in the field of orthopaedics.

2. Nanotechnology in Orthopaedic

Nanotechnology encompasses the manipulation, design and application of materials and structures at the nanoscale, typically spanning 1 to 100 nanometres. This field exploits the unique properties of these tiny scales, where quantum effects and surface interactions play a key role. By engineering materials at such dimensions, scientists hope to create new functions and properties unavailable in bulk materials. Nanotechnology permeates fields as diverse as medicine, electronics, energy and materials science, helping to create customised materials, devices and systems with greater performance, precision and efficiency. Researchers use specialised tools and techniques to scrutinise, manipulate and understand the matter at the nanoscale, thus opening up new avenues for innovation and scientific progress.

The convergence of nanotechnology and orthopaedics heralds a transformative era that will redefine the paradigm for the diagnosis, treatment and rehabilitation of musculoskeletal disorders. Nanotechnology provides precision-engineered solutions at the nanoscale by crafting materials and structures atom by atom. This advancement results in implants that mirror the complexity of natural bone, facilitating seamless integration, reducing rejection rates, and improving mechanical stability. The innovation of nanotechnology also extends to personalised therapies, where implants are customised through advanced imaging and 3D printing techniques to optimise implant fit, function and patient health. The impact of nanotechnology goes beyond structural improvements to revolutionise drug delivery by targeting the diseased area with nanoparticles, inhibiting systemic side effects and enhancing therapeutic efficacy [3]. Nanoscale imaging also improves diagnosis by revealing intricate bone microstructure, mineralisation abnormalities and cellular dynamics, thus ensuring timely intervention. In conclusion, nanotechnology has advanced orthopaedic surgery by rejuvenating implant design, enabling tailored treatments, improving drug delivery methods, and increasing diagnostic refinement, thereby improving the lives of patients with musculoskeletal disorders.

The study conducted by Balasundaram, Ganesan, and Webster underscores nanotechnology's potential in bone repair, capitalizing on its distinct properties at the nanoscale that enable more favorable interactions between nanomaterials, cells, and tissues [4]. These interactions play a pivotal role in promoting essential processes like cell adhesion, proliferation, and differentiation, all of which are integral to bone regeneration. The incorporation of nanotechnology enables the creation of biomaterials mimicking natural bone matrices, enhancing biocompatibility and facilitating successful tissue integration.

A key focus of this case study is the role of nanotechnology in designing scaffolds and implants with improved structural and mechanical attributes. By manipulating materials at the nanoscale, researchers enhance the durability of biomaterials, ensuring they can withstand physiological forces.

These nanoscale refinements not only extend implant lifespan but also contribute to the restoration of bone strength and functionality.

The study also emphasizes nanotechnology's impact on targeted drug delivery for bone repair. Engineered nanoparticles can encapsulate growth factors, enabling their sustained release at repair sites. This targeted delivery accelerates tissue regeneration while minimizing the risk of systemic side effects, presenting a more efficient and patient-friendly treatment approach.

Furthermore, the case study underscores the potential of nanotechnology-enhanced imaging for precise diagnosis and monitoring of bone repair processes. Nanoscale imaging technologies provide unprecedented insights into bone microstructure, tissue regeneration progress, and cellular interactions. Such comprehensive understanding aids clinicians in making informed decisions regarding interventions. This research showcases the transformative potential of nanotechnology and biomaterials in Orthopaedics applications, offering innovative avenues for enhancing bone repair strategies and ultimately improving patient outcomes.

3. Biomaterials in Orthopaedics

Biomaterials, whether of natural origin or synthetic, are designed to interact seamlessly with biological systems for medical and biological purposes. These substances can be integrated with living tissues, organs or biological systems for therapeutic, diagnostic or research purposes while minimising the impact on the host organism. In modern healthcare, biomaterials serve as a bridge between medicine, materials science and biology, contributing significantly to medical interventions and various applications. The roles of biomaterials include promoting tissue regeneration, supporting wound healing, enhancing structures and delivering therapeutic agents [5]. Careful consideration of biocompatibility and mechanical properties is required during the design process to ensure that the material is in harmony with the biological system and meets the specific application requirements. From synthetic polymers to natural compounds such as collagen and chitosan, biomaterials play a pivotal role in tissue engineering, regenerative medicine, medical devices and drug delivery systems, ultimately contributing to patient care and well-being.

Orthopaedics harnesses a diverse range of biomaterials, each meticulously tailored to serve specific applications and functions. Among these biomaterials are ceramics, such as hydroxyapatite and calcium phosphate, which closely resemble natural bone minerals. Renowned for their biocompatibility, these compounds find application in bone grafts and implant coatings, promoting seamless integration with bone structures.

Synthetic polymers, exemplified by polyethylene and polyurethane, offer a pliant arsenal for joint replacements and fracture fixation. Their flexibility and harmonious interaction with bone tissues contributes to reduced inflammation and wear. Metallic materials, including titanium, stainless steel, and cobalt-chromium alloys, are sought for their robust mechanical properties. These alloys excel in fabricating joint prostheses and plates, benefiting from their compatibility with medical imaging.

Composite biomaterials, born from the fusion of ceramics or polymers with metallic reinforcements, leverage the unique strengths of each component. This alliance enhances both mechanical strength and biocompatibility. Biodegradable biomaterials, like polylactic acid (PLA) and polyglycolic acid (PGA), elegantly degrade over time, gradually transferring load to healing bone [6]. These biomaterials play a role in tissue scaffolds and fracture fixation.

Bioactive materials, such as bioactive glass and glass ceramics, stimulate tissue growth and integration. Found in bone grafts and coatings, these compounds expedite the healing process [7]. The spectrum extends to natural biomaterials like collagen, chitosan, and silk, esteemed for their biocompatibility and ability to stimulate cell adhesion. These biomaterials bolster tissue engineering and wound-healing endeavors.

Within the realm of Orthopaedics, the selection of biomaterials hinges on multifaceted considerations, encompassing mechanical requirements, biocompatibility, degradation kinetics, and the intended therapeutic purpose. The orchestration of this diverse array of biomaterials fueled innovation, propelling Orthopaedics interventions towards heightened efficacy and amplified patient outcomes. The strategic deployment of these materials ushers in a new era of Orthopaedics advancements, where personalized treatments and functional implants define the landscape of care.

The integration of magnesium as a biomaterial in Orthopaedics presents a promising avenue for advancing bone repair and regeneration. The comprehensive review conducted by Walker, Jemimah, et al. sheds light on the distinctive attributes of magnesium-based biomaterials in reshaping Orthopaedics approaches [8]. This study emphasizes their biological implications and contributions to the field.

The focus of the case study lies in highlighting magnesium biomaterials' significance in Orthopaedics due to their inherent properties. Magnesium's biocompatibility, ability to degrade naturally, and mechanical resemblance to bone make it an intriguing choice for bone-healing implants and scaffolds.

One of the pivotal aspects underscored by the research is the intricate biological considerations associated with magnesium biomaterials. While magnesium’s-controlled biodegradability is advantageous, its rapid corrosion rate poses challenges. The release of magnesium ions can stimulate bone formation, although excessive release may lead to cytotoxicity. Striking the right balance is essential to harness the therapeutic potential of magnesium effectively.

In a clinical context, the study explores the prospects of magnesium biomaterials. Their application holds promise in Orthopaedics procedures, fracture repair, and bone tissue engineering. Design optimization of magnesium-based implants is pivotal to ensure biocompatibility, controlled degradation, and successful bone integration.

The case study also underscores the prospects of magnesium biomaterials in reshaping the Orthopaedics landscape, advocating for ongoing research. Walker et al.'s study underscores the dynamic potential of magnesium integration in Orthopaedics applications, offering novel avenues for enhanced bone healing and regeneration. The above work provides valuable insights into the potential of magnesium-based implants, devices, and scaffolds to advance Orthopaedics interventions. This case study underscores the intricate balance between the biological impacts and clinical utility of magnesium biomaterials, inspiring continued research to unlock their full therapeutic potential in Orthopaedics medicine.

4. The Intersection of Nanotechnology and Biomaterials in Orthopaedics

The confluence of nanotechnology and biomaterials represents a transformative juncture within biomedical science. This dynamic amalgamation harnesses the distinctive attributes inherent to nanoscale materials to augment and optimize the properties and efficacy of biomaterials, ushering forth paradigm-shifting breakthroughs across a broad spectrum of medical disciplines. At the crux of this symbiotic interplay lies the precision afforded by nanotechnology, enabling meticulous manipulation of materials at the nanoscale. This precision confers the capacity to engineer biomaterials with meticulously tailored characteristics, thereby endowing them with heightened mechanical resilience, an expanded surface area, and augmented reactivity. These enhancements collectively amplify the versatility and utility of biomaterials, spanning a wide gamut of medical applications.

The application of nanotechnology extends further to the modification of biomaterial surfaces at the nanoscale, leading to profound improvements in biocompatibility. This manipulation curtails the propensity for adverse reactions while simultaneously enhancing cellular adhesion [9]. And the introduction of functionalized nanocoatings demonstrates efficacy in mitigating bacterial adhesion, an attribute of paramount significance in extending the lifespan of implants and mitigating the risks of infections.

A pivotal facet where nanotechnology has wrought transformation is in drug delivery mechanisms. This innovation enables the imbuing of biomaterials with the capability to precisely regulate drug release kinetics. The integration of therapeutic agents within nanoparticles facilitates targeted delivery to specific affected regions, thereby curtailing systemic side effects and markedly enhancing the therapeutic efficiency of treatments. Furthermore, the fusion of nanotechnology with biomaterials holds immense promise in tissue regeneration. Nanoengineered scaffolds, designed to mimic the intricate structure of natural extracellular matrices, foster an environment conducive to the proliferation and differentiation of cells. This orchestrated milieu expedites the tissue rejuvenation process, imparting a new dimension to regenerative medicine. Notably, the introduction of nanoparticles into biodegradable biomaterials introduces the ability to modulate degradation rates. This phenomenon significantly influences the longevity of the material while concurrently facilitating the controlled release of therapeutic agents throughout the degradation trajectory, thereby enhancing the therapeutic impact [10].

Nanotechnology's influence extends to the domain of diagnostics as well. It enables precision imaging at the nanoscale, unveiling intricate facets of biomaterial interactions within biological tissues. This capability furnishes critical insights that contribute to a comprehensive understanding of the behavior and interaction of biomaterials within the complex biological milieu. However, despite the notable advancements, integrating nanotechnology into biomaterials presents challenges, including potential nanomaterial toxicity and intricate regulatory considerations. Nevertheless, ongoing research endeavors steadfastly address these concerns while harnessing the immense potential of nanotechnology.

In summation, the harmonious amalgamation of nanotechnology and biomaterials propels the realm of biomaterials into an echelon characterized by heightened performance and unparalleled utility. This synergistic union paves the way for a new era of innovative medical interventions, characterized by personalized treatments, superior implant materials, and pioneering drug delivery systems. The overarching aspiration remains the enhancement of patient outcomes and the elevation of quality of life, marking a transformative juncture within the annals of medical science.

The strategic amalgamation of porous biomaterials and nanotechnology has emerged as a pivotal avenue for advancing Orthopaedics treatments. The work authored by Babaie and Bhaduri elucidates the significance of porous biomaterials in Orthopaedics and underscores the role of nanotechnology in enhancing their properties and functionalities [11].

Porous biomaterials have garnered traction within Orthopaedics due to their ability to emulate natural bone structures. Babaie and Bhaduri's review accentuates their value in facilitating tissue integration, cell adhesion, and nutrient exchange. This porous architecture supports bone regeneration and endows implants with mechanical compatibility, paving the way for improved clinical outcomes. In this narrative, nanotechnology emerges as a transformative catalyst. By harnessing nanoscale materials and engineering techniques, the paper elucidates how nanotechnology contributes to the fabrication of porous biomaterials with unprecedented precision. Nanotechnology facilitates the generation of nanoscale features on biomaterial surfaces, resulting in heightened surface area, augmented cellular interaction, and optimized mechanical traits. Furthermore, the paper accentuates nanotechnology's role in tailoring biomaterial porosity. Nanoscale control over porosity enables the creation of scaffolds boasting optimal pore size distribution, promoting nutrient diffusion and cellular infiltration. This fine-tuned control amplifies the biomaterials' regenerative potential and seamless integration with host tissues.Another dimension highlighted is the integration of nanomaterials within porous biomaterials. Strategic introduction of nanoparticles and nanocomposites enhances mechanical strength, drug delivery capabilities, and antimicrobial attributes. This integration begets multifunctional biomaterials with tailored attributes aligned with specific clinical requirements.

The deliberate fusion of the above word realms endows Orthopaedics with innovative solutions, ranging from regenerative scaffolds to amplified implant performance. This case study underscores the synergistic promise of porous biomaterials and nanotechnology, delineating a promising trajectory for advancing Orthopaedics care through this symbiotic convergence.

5. Future Perspectives

The harmonious integration of nanotechnology and biomaterials within the realm of Orthopaedics heralds an era of unprecedented innovation and vast potential. This intricate synergy possesses the transformative capacity to not only reshape the conceptualization and execution of Orthopaedics treatments but also to redefine the overall patient experience.

At the vanguard of this convergence lies the notion of precision implants. The amalgamation of nanotechnology and biomaterials introduces a new era of personalized implant solutions. By leveraging advanced imaging techniques and harnessing the capabilities of 3D printing, Orthopaedics interventions can be intricately tailored to the unique anatomical characteristics of each individual. This innovative approach transcends conventional methodologies, ensuring a level of fit, functionality, and comfort previously inconceivable.

The ramifications of this symbiotic relationship extend to the forefront of regenerative therapies. Through the merger of nanotechnology and biomaterials, the Orthopaedics field is poised to pioneer treatments that transcend traditional paradigms. The manipulation of biomaterials at the nanoscale enables them to intricately mimic native tissues, thereby fostering crucial cellular processes like proliferation and differentiation. As a result, the body's innate healing trajectory is accelerated, holding remarkable promise for the evolution of regenerative medicine. Nanotechnology also redefines the landscape of drug delivery in Orthopaedics. Through precise engineering, nanoparticles can encapsulate therapeutic agents, ushering in a new era of targeted drug release. This approach effectively minimizes systemic side effects while maximizing the therapeutic impact, signifying a noteworthy advancement in Orthopaedics pharmaceuticals. Furthermore, the infusion of nanotechnology into biomaterials fundamentally transforms the process of implant integration. Nanoengineered surface modifications enhance cellular adhesion, thereby mitigating the risks of implant rejection. Additionally, antimicrobial coatings, directly derived from nanotechnology, effectively counteract the potential for post-operative infections and consequently extend the lifespan of implants. Diagnostic precision also greatly benefits from the amalgamation of nanotechnology and biomaterials. State-of-the-art nanoscale imaging techniques furnish unprecedented insights into intricate bone microarchitecture and the dynamics of disease, thereby equipping medical professionals with the requisite information for timely and effective interventions. Moreover, nanotechnology introduces the exciting prospect of real-time monitoring facilitated by embedded sensors within biomaterials. These "smart" implants offer clinicians real-time information pertaining to factors like load distribution and the progression of healing, thereby facilitating patient-centric decision-making.

While the journey towards the realization of this transformative convergence is replete with promise, it also presents its share of challenges. Considerations such as biocompatibility, the navigation of regulatory landscapes, and the potential toxicity of nanomaterials loom as significant obstacles. Nevertheless, the persistent endeavors of dedicated researchers continue to redefine solutions, ensuring the prudent and effective utilization of this innovative amalgamation. In synthesis, the interplay of nanotechnology and biomaterials possesses the potential to fundamentally reshape the very landscape of Orthopaedics. Personalized implants, regenerative therapies, optimized drug administration, and precise diagnostics stand as the hallmark achievements of this transformative journey. Through unceasing innovation and unwavering perseverance, this symbiotic fusion aspires to redefine Orthopaedics, ultimately optimizing patient outcomes and charting a trajectory towards an elevated quality of life.

The convergence of nanotechnology and biomaterials within the realm of Orthopaedics presents a pivotal juncture characterized by transformative possibilities. This intricate interplay holds the potential to usher in a new era of innovation and efficacy in Orthopaedics treatments, heralding a paradigm shift in the way medical interventions are conceived, executed, and experienced. However, this amalgamation of nanotechnology and biomaterials does not come without its array of intricate challenges and inherent limitations. These challenges necessitate a meticulous and informed approach that acknowledges the multifaceted nature of the terrain ahead. By adopting a measured stance and addressing these challenges head-on, the Orthopaedics community can navigate these obstacles while harnessing the full transformative potential that lies within the fusion of nanotechnology and biomaterials. One of the primary challenges pertains to the critical aspect of ensuring biocompatibility. The intricate synergy between nanomaterials and biological systems triggers concerns surrounding potential toxicity and the compatibility of these engineered materials with living organisms. The paramount importance of carefully assessing and verifying biocompatibility cannot be understated, as it directly influences the safety and efficacy of nanotechnology-driven biomaterials within the Orthopaedics domain. The complex regulatory landscape governing the utilization of nanotechnology and biomaterials in medical applications adds another layer of complexity to this convergence. These regulations are dynamic and ever-evolving, necessitating meticulous attention to detail when integrating novel technologies into clinical practice. Standardizing protocols and guidelines are essential to guarantee patient safety and harmonize research efforts with the prevailing clinical framework, ensuring a seamless transition from the laboratory to real-world applications.

While the potential for groundbreaking innovation showcased in laboratory settings is tantalizing, the translation of nanotechnology-driven biomaterials into tangible clinical solutions is a multifaceted endeavor. Scaling up production from experimental realms to practical clinical applications requires a delicate balance between trailblazing advancements and the operational efficiency required for large-scale production. Bridging this gap is essential for ensuring that the transformative potential of nanotechnology and biomaterials can be harnessed to its fullest extent within the Orthopaedics landscape.

In conclusion, the fusion of nanotechnology and biomaterials has positioned Orthopaedics on the precipice of transformative possibilities. Yet, the journey ahead is replete with challenges that necessitate a cautious and informed approach. By acknowledging the importance of biocompatibility, navigating the evolving regulatory landscape, and bridging the gap between laboratory innovation and clinical realization, the Orthopaedics field can navigate these complexities while unlocking the vast potential that the synergy of nanotechnology and biomaterials offers for reshaping patient care.

6. Conclusion

To recapitulate, this discourse has delved into the profound influence of combining nanotechnology and biomaterials in reshaping the landscape of Orthopaedic medical applications. It has highlighted the transformative potential of nanotechnology in precision implant design, regenerative therapies, drug delivery, and diagnostics. The symbiotic integration of nanotechnology and biomaterials has yielded advancements that address critical challenges in Orthopaedics, such as biocompatibility and implant longevity. These advancements hold the promise of enhancing patient outcomes and redefining the standards of care. Looking forward, the future of Orthopaedics lies in the continued exploration and refinement of these innovative approaches. By strategically navigating the complexities of biocompatibility, regulations, and scalability, the field can harness the full potential of nanotechnology and biomaterials to usher in an era of personalized treatments and improved quality of life for patients with musculoskeletal disorders.

References

[1] Zhang, Y. et al. Dental implant nano-engineering: Advances, limitations and future directions. Nanomaterials, 2021, 11(10): 2489.

[2] Zhang, Y. et al. Stem cell-friendly scaffold biomaterials: Applications for Bone Tissue Engineering and regenerative medicine. Frontiers in Bioengineering and Biotechnology, 2020, 8.

[3] Lee, N.K., Kim, S.-N. And Park, C.G. Immune cell targeting nanoparticles: A Review. Biomaterials Research, 2021, 25(1).

[4] Balasundaram, G. and Webster, T.J. Nanotechnology and biomaterials for Orthopaedics medical applications. Nanomedicine, 2006, 1(2): 169-176.

[5] Farag, M.M. Recent trends on biomaterials for tissue regeneration applications: Review. Journal of Materials Science, 2023, 58(2): 527-558.

[6] Elmowafy, E.M., Tiboni, M. and Soliman, M.E. Biocompatibility, biodegradation and biomedical applications of poly (lactic acid)/poly (lactic-co-glycolic acid) micro and nanoparticles. Journal of Pharmaceutical Investigation, 2019, 49(4): 347-380.

[7] Cannillo, V. et al. Editorial: Bioceramics and/or bioactive glass-based composites. Frontiers in Materials, 2021, 8.

[8] Walker, J. et al. Magnesium biomaterials for Orthopaedics application: A review from a biological perspective. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 2014, 102(6): 1316-1331.

[9] Sanità, G., Carrese, B. and Lamberti, A. Nanoparticle surface functionalization: How to improve biocompatibility and cellular internalization. Frontiers in Molecular Biosciences, 2020, 7.

[10] Qu, W., Qader, I.B. and Abbott, A.P. Controlled release of pharmaceutical agents using eutectic modified gelatin. Drug Delivery and Translational Research, 2021, 12(5): 1187-1194.

[11] Babaie, E. and Bhaduri, S.B.Fabrication aspects of porous biomaterials in Orthopaedics Applications: A Review. ACS Biomaterials Science & Engineering, 2017, 4(1): 1–39.