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Drug delivery systems for osteogenic disorders utilizing green nanotechnology

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Abstract--Background: The skeletal system, crucial for structural support, movement, and various metabolic processes, is continually remodeled through the balanced activity of osteoblasts, osteocytes, and osteoclasts. Disruptions in this balance lead to bone disorders, including osteoporosis and osteogenesis imperfecta, necessitating effective therapeutic strategies. Traditional drug delivery systems face challenges such as poor targeting efficiency and systemic toxicity. Aim: This review examines the application of green nanotechnology in developing advanced drug delivery systems for treating osteogenic disorders. Green nanotechnology focuses on using environmentally friendly methods to synthesize nanomaterials (NMs) that enhance drug delivery and promote bone regeneration while minimizing toxicity. Methods: The review evaluates various nanotechnology-based drug delivery systems, including bisphosphonates, tetracyclines, oligopeptides, and aptamers, and their applications in bone health. It highlights the limitations of conventional approaches and the potential of green nanotechnology to overcome these challenges. The review covers polysaccharide-based, protein-based, calcium-based, and silica-based green nanotechnologies and their roles in improving drug delivery for bone disorders. Results: Green nanotechnology has demonstrated significant promise in enhancing drug delivery for osteogenic disorders. Polysaccharide-based systems, such as heparin and chitosan nanocomplexes, offer improved targeting and drug release capabilities. Protein-based technologies, including silk sericin and collagen, support bone repair and regeneration. Calcium-based systems, such as DNA-loaded calcium phosphate nanoparticles, show

potential in gene delivery and osteoblast differentiation. Silica-based systems provide controlled drug release and multifunctional applications. Conclusion: Green nanotechnology offers a transformative approach to drug delivery for bone disorders, addressing the limitations of traditional systems. By utilizing environmentally friendly synthesis methods and enhancing targeting and drug release, green nanotechnology holds the potential to revolutionize treatment strategies for osteogenic disorders. Future research should focus on optimizing these technologies and expanding their clinical applications to improve patient outcomes.

Keywords--Green nanotechnology, drug delivery systems, osteogenic disorders, nanomaterials, bone regeneration, environmentally friendly synthesis.

Introduction

The skeletal system serves as the internal framework of the human body, performing essential functions necessary for survival, such as structural support, movement, protection, hematopoiesis, calcium homeostasis, and endocrine regulation. Alongside cartilage, bone constitutes a key component of the skeletal system—an active organ continually undergoing remodeling to ensure the effective and enduring performance of its critical functions [1,2]. Consequently, it is crucial for bone to adapt to mechanical variations caused by changing environmental conditions. Bone tissue consists of three distinct types of bone cells: osteoblasts and osteocytes, which play central roles in bone formation and mineralization, and osteoclasts, which are responsible for bone resorption. Bone is broadly categorized into cortical and trabecular types, with cortical bone being denser, whereas trabecular bone is predominantly involved in remodeling and thus represents the primary site for bone disorders [3,4]. Bone disorders involve pathological changes to the skeletal system. Typically, bone mass is regulated through bone resorption, a process where osteoclasts degrade bone tissue and release minerals, leading to subsequent bone formation through a systematic remodeling process [5]. However, this balance can be disrupted by various factors, including genetic and phenotypic influences, resulting in abnormal bone remodeling and the emergence of bone disorders [5].

Advances in medical research have significantly improved both the prevention and treatment of various bone disorders. Numerous medicinal compounds, along with surgical and therapeutic interventions, have been developed. This review focuses specifically on drug delivery systems designed to address bone diseases, excluding therapy-based and surgical treatments from discussion. Drug delivery systems refer to technologies that facilitate the transport of pharmaceutical agents within the body to achieve the desired therapeutic outcomes safely. In the context of bone health, drug delivery systems can be classified into two categories based on their target: the entire skeletal system, or "bonesites," and specific cellular locations within bone tissue [16]. Bone-targeting molecules, which can be either synthetic or biological, are designed to prevent bone tissue loss and support bone regeneration [17]. These drugs typically exhibit high stability upon

reaching the targeted tissue and demonstrate an affinity for bone mineral at minimal systemic levels [18].

2.1. Delivery of Bisphosphonates (BPs)

Bisphosphonates (BPs) are widely utilized non-specific chemically synthesized drugs, derived from inorganic pyrophosphates, which are phosphorus oxyanions characterized by a P-O-P linkage. These pyrophosphates are natural compounds that regulate bone mineralization by binding to hydroxyapatite (HA) crystals [19]. Due to their high affinity for calcium phosphate (CP), BPs effectively inhibit bone resorption, making them valuable in the treatment of bone disorders such as osteoporosis and osteogenesis imperfecta [20]. BPs are typically administered intravenously every 3–4 weeks or orally on a daily basis [21]. Alternatives to these administration routes include microencapsulation of BPs within biodegradable poly(lactic-co-glycolic acid) (PLGA) or their association with biomaterials, either in free or microencapsulated form, which can be implanted or conjugated. Systemic administration of BPs usually results in 20–50% deposition at bone tissues, with minimal accumulation in other areas [22,23].

2.2. Tetracyclines (TCs)

Tetracyclines (TCs) are broad-spectrum antibiotics used to address various bacterial bone infections [24]. They can be directly extracted from certain *Streptomyces* bacteria species or produced semi-synthetically from these isolated compounds, resulting in a diverse array of compounds within the same antibiotic family. TCs inhibit bone resorption, block collagenase activity that breaks peptide bonds in collagen, and stimulate osteoblast formation [25]. As a result, TCs are predominantly used to manage periodontitis, which is associated with alveolar bone loss [26]. TCs can be administered both systemically and locally, the latter offering the advantage of mitigating the adverse effects associated with systemic administration, such as the development of antibiotic-resistant flora and suppression of normal microbial flora [27]. Effective local drug delivery methods involve combining TCs with fibers [28] or bioactive glass [29], as well as encapsulating TCs within PLGA [30] or PEG-PLGA micelles [31], which allows for controlled release in the targeted infected area.

2.3. Oligopeptides

Oligopeptides are short amino acid sequences naturally occurring in the human body, capable of binding to hydroxyapatite (HA) when they contain aspartic acid (Asp) and glutamic acid (Glu) residues. This binding action helps inhibit bone resorption [32,33]. Key non-collagenous bone proteins such as osteopontin and bone sialoprotein, which include repetitive sequences of L-Asp and L-Glu, respectively, facilitate rapid binding to HA upon secretion into osteoblastic cell cultures. Thus, these oligopeptides are promising candidates as bone-targeting agents, potentially combined with various drugs. For example, a drug labeled with an oligopeptide can be systemically administered to selectively target bone, where it binds and gradually releases the active compound during the bone remodeling process [34–36].

2.4. Aptamers

Nucleic acid aptamers are short, single-stranded DNA or RNA molecules selected for their ability to bind to specific targets [37]. Aptamers function as chemical antibodies due to their similar functional properties to traditional antibodies but offer enhancements in mechanical and chemical characteristics. They exhibit high selectivity and specificity in target recognition and binding, are relatively small, and have a flexible structure. Additionally, aptamers are characterized by rapid chemical production, ease of chemical modification, high stability, and lack of immunogenicity. Many aptamers can also be internalized after binding to cellular receptors, making them effective for targeted delivery of small interfering RNA (siRNA), microRNA, and conventional drugs—particularly valuable for treating bone diseases. Various cell-type-specific aptamers have been conjugated with therapeutic agents (such as siRNA, microRNA, chemotherapeutics, or toxins) or delivery vehicles (e.g., organic or inorganic nanocarriers) for targeted delivery [37,38]. A recent proof-of-concept study developed aptamer-functionalized lipid nanoparticles (LNPs) for siRNA delivery. Using cell-based systematic evolution of ligands by exponential enrichment (SELEX), DNA aptamers targeting osteoblasts were employed to decorate LNPs encapsulating siRNAs. This delivery system facilitated osteoblast-selective siRNA uptake *in vivo*, leading to gene silencing, which promoted bone formation, improved bone microarchitecture, and enhanced the mechanical properties of the newly formed tissue [37,39].

2.5. Challenges to Current Drug Delivery Approaches for Bone Diseases

Bone disorders, including trauma, osteoporosis, and osteogenesis imperfecta, collectively result in approximately 6 million fractures annually in the United States. Between 5% and 10% of these fractures lead to delayed union or nonunion, with age, smoking, and diabetes being common comorbidities that impair healing [38,40]. Effective bone regeneration necessitates a coordinated interplay of cells and growth factors, alongside precise drug targeting within the tissue. Although innovative drug delivery methods have achieved varying degrees of clinical success, substantial technological challenges remain.

Bone disorders frequently necessitate clinical interventions, the results of which are not always optimal. Some prevalent skeletal disorders lack effective treatments, while others exhibit a problematic balance between adverse reactions and therapeutic benefits. Systemic drug delivery methods often struggle with poor bone tissue penetration, leading to potential systemic toxicity [41]. Many commonly used drugs face significant challenges in reaching the target tissue, necessitating higher doses that exacerbate the risk of toxicity [16]. For example, patients undergoing treatment with anti-osteoporotic drugs are at increased risk of adverse effects such as cancer and endometritis due to the high doses required [42]. This underscores the urgent need for the development of more efficient drug delivery systems that minimize toxicity.

3. Nanotechnology as a Solution for the Treatment of Bone Disorders

Nanomedicine bridges the gap between nanotechnology and human physiology, enabling scientists and researchers to explore biological systems at the nanoscale

with the goal of transforming traditional therapies. This is achieved by enhancing drug delivery strategies to better mimic natural, healthy tissues [16]. The advent of nanotechnology has raised high expectations for addressing complexities in medicine and biological sciences. The integration of nanomaterials (NMs) into medicine has spurred the growth of nanomedicine, offering significant promise for the treatment of various diseases, including bone disorders. Consequently, NMs are emerging as a promising approach for treating bone disorders, addressing many limitations of current therapies. Advanced drug delivery systems based on nanotechnology play a crucial role in osteogenic bone disorders, offering potential improvements in the repair of degenerated and injured tissues [43,44]. Many components in bone tissue exist at the nanometer scale, and self-assembled nanostructured extracellular matrix (ECM) substrates can closely interact with bone-forming cells, promoting their adhesion, proliferation, and differentiation [45,46].

The literature is rich with examples of NM-based targeted drug delivery systems that enhance bone regeneration due to their small size, which allows them to navigate biological barriers for more efficient delivery [47,48]. Nanotechnology-based drug delivery begins with the creation of drug-loaded NPs, which offer a promising approach for extending circulation time and improving drug biodistribution [89]. NPs can be easily applied during surgical procedures on injured bone sites. They can also serve as therapeutic delivery agents or be integrated into nanoengineered biomaterials, such as electrospun supports, to expedite the bone regeneration process. Recent research has also explored combinatorial nano-based approaches, demonstrating a synergistic effect for both therapeutic delivery and tissue regeneration [90]. In the context of bone disorders, NMs can provide scaffolds that facilitate tissue regeneration through mechanical stimulation. This process involves the release of various drugs and mediators or 3D scaffolds that support the growth and differentiation of bone marrow stem cells into osteocytes [44].

Efficiently targeting bone-specific drugs to the desired site of action can enhance efficacy and reduce toxicity across various osteogenic disorders. However, challenges include maintaining drug functionality and avoiding adverse side effects [16]. A major issue with NM-based drug delivery approaches is the production of delivery vehicles. Traditional NM synthesis methods often involve physicochemical processes with several drawbacks, such as harsh processing conditions, production of toxic by-products, and inadequate biocompatibility, leading to unwanted cytotoxicity upon contact with biological tissues [91–93]. Moreover, specialized instrumentation, such as chemical vapor deposition (CVD) chambers or ultra-high vacuum systems, is often required for production. Additional challenges include NP aggregation post-synthesis, which complicates purification and characterization, potentially compromising the effectiveness of the synthesized NMs for biomedical applications [94]. Some NMs may degrade in the body, generating toxic degradation products that could harm tissues or alter local pH levels. Therefore, using these materials in large doses can be problematic. Furthermore, due to the complexity of bone tissue, many drug delivery systems exhibit poor targeting efficiency and uncontrolled drug release. To improve therapeutic efficiency and biomedical outcomes, there is a strong

push towards developing new targeted drug delivery systems that address these limitations.

4. Green Nanotechnology as a Pioneering Approach for the Treatment of Osteogenic Disorders

Nanotechnology is increasingly recognized as a viable alternative to address global environmental and healthcare challenges. However, the nanoscale realm faces its own set of challenges, particularly concerning the sustainable production of nanomaterials (NMs) [35,95]. In response, Green Nanotechnology has emerged as a promising approach by applying the 12 principles of green chemistry [96] to NM synthesis. Green Nanotechnology focuses on producing NMs using living organisms, biomolecules, or natural waste materials, and follows methods designed to reduce or eliminate the use of harmful substances, such as solvents, reducing agents, and capping agents [97–99].

In the field of nanomedicine, NMs synthesized through green methods have shown significant potential as antimicrobial and anticancer agents. These green-synthesized NMs also offer capabilities in photoimaging and photothermal therapy, magnetically responsive drug delivery systems, and as nanodetectors for biomolecules and complex biological structures [100–102]. Despite its nascent stage, the application of green nanotechnologies for treating bone disorders is an emerging field. Although public awareness is limited, recent research highlights promising trends in using green NMs for diagnosing and treating osteogenic disorders. These advancements emphasize improved targeting methods compared to traditionally synthesized NMs and underscore the potential benefits of this innovative green technology. The subsequent sections will explore the biomolecules used in the production and assembly of green NMs for drug delivery systems aimed at treating various osteogenic disorders.

4.1. Polysaccharide-Based Green Nanotechnologies

Polysaccharides, as versatile and abundant natural molecules, hold significant potential for biomedical applications, particularly in drug delivery systems for bone disorders. This section highlights various polysaccharide-based green nanotechnologies, emphasizing their potential benefits and applications in treating osteogenic disorders.

1. Heparin-Based Nanocomplexes: Heparin, a naturally occurring glycosaminoglycan, is known for its high loading capacity and enhanced release abilities. Liu et al. developed heparin-based nanocomplexes for delivering placental growth factor (PIGF) and bone morphogenic protein-2 (BMP-2). The nanocomplexes, made with heparin and N-(2-hydroxyl) propyl-3-trimethyl ammonium chitosan chloride (HTCC), exhibited high loading efficiencies (83–99%) and a size of approximately 350 nm. In vitro assays showed that PIGF-2 had osteogenic effects similar to BMP-2, suggesting that heparin-based nanocomplexes could enhance osteoblast functionality and support bone regeneration [103].

Kim et al. also explored heparin-conjugated PLGA nanoparticles for bone regeneration. The heparin-conjugated nanoparticles, sized below 520 nm, effectively released BMP-2 over a two-week period, promoting the differentiation of bone marrow-derived mesenchymal stem cells (BMMSCs) into osteogenic cells.

The study found that these nanoparticles, combined with BMMSCs, induced extensive bone formation, outperforming BMP-2-loaded nanoparticles and osteogenically differentiated BMMSCs [104].

2. Chitosan-Based Nanoparticles: Chitosan, a polysaccharide derived from shellfish exoskeletons, is utilized in various drug delivery systems. Lee et al. developed PLGA-lovastatin-chitosan-tetracycline nanoparticles (NPs) for local drug delivery. These nanoparticles, with a size around 107 nm, released tetracyclines and lovastatin to control infections and promote bone regeneration in periodontitis. The initial burst release of tetracyclines was followed by a gradual release, and in vitro tests showed excellent biocompatibility and enhanced new bone formation [105]. Valente et al. created a cost-effective delivery system using chitosan, dextran, and bovine serum albumin (CH-Dext-BSA) nanoparticles. This system combined proteins and cells in one carrier, improving the protection and transportation of biomolecules and promoting bone regeneration. The system also allowed for the encapsulation of autologous patient cells, which could enhance tissue repair [106]. Gaur et al. demonstrated the chitosan nanoparticle-mediated delivery of miR-34a, which inhibited prostate tumor growth and preserved bone integrity in both in vitro and in vivo studies [107].

3. Chitosan-Grafted Titanium Substrates: Chitosan-grafted titanium substrates (Ti-CS-BMP2) were studied for their ability to enhance bone marrow stromal cell (BMSC) adhesion and differentiation into osteoblasts. This substrate retained BMP2 and released it slowly, promoting osteoblast function and tissue integration [108]. Similarly, carboxymethyl chitosan (CMCS) was grafted onto titanium alloy substrates, which enhanced cell attachment, alkaline phosphatase (ALP) activity, and calcium mineral deposition while reducing bacterial adhesion [109].

4. Pullulan-Based Nanogels: Pullulan, a polysaccharide polymer, was used to create cholesteryl group and acryloyl group-bearing pullulan (CHPOA) nanogels. These fast-degradable hydrogels were employed for controlled release of BMP2 and recombinant human fibroblast growth factor 18 (FGF18), promoting effective bone repair [110].

5. Gellan Xanthan Gum-Based Systems: Gellan xanthan gum, an anionic polysaccharide, was combined with chitosan nanoparticles and growth factors (bFGF and BMP7) in a dual growth factor delivery system. This system promoted the differentiation of human fetal osteoblasts and showed antibacterial effects against common pathogens, enhancing bone regeneration and reducing implant failure risks [111,112].

6. Alginate-Based Gene-Activated Constructs: Alginate, an anionic polysaccharide from brown seaweed, was used to create gene-activated constructs encapsulating plasmid DNA encoding for TGF- β 3, BMP2, or both. These constructs supported nonviral gene transfer and directed mesenchymal stem cells (MSCs) towards chondrogenic or osteogenic phenotypes, showing potential for bone tissue engineering [115]. Overall, polysaccharide-based green nanotechnologies offer promising solutions for bone disorder treatments by enhancing drug delivery, improving targeting efficiency, and promoting bone regeneration while adhering to environmentally sustainable practices.

4.2. Protein-Based Green Nanotechnologies

Protein-based green nanotechnologies leverage biologically-derived proteins for the creation and functionalization of nanoscale structures with significant

potential in biomedical applications, including bone repair. Here are notable examples of protein-based approaches in drug delivery systems for osteogenic disorders:

1. Silk Sericin (SS): Silk sericin, a glycoprotein produced by *Bombyx mori* silkworms, exhibits diverse functional groups and bioactive properties useful for bone repair and tissue engineering. Nishida's group demonstrated the use of SS films incorporated with fibroblast growth factor-2 (FGF2) for skull defect repair in rats. The films released FGF2 in a sustained manner due to enzymatic hydrolysis, supporting tissue growth around skull wounds and enhancing bone remodeling and wound healing [117]. In another study, SS was combined with chitosan and β -glycerophosphate (β -GP) to create hydrogels loaded with longan seed extract (LE). The incorporation of SS influenced the hydrogel network, leading to a more rapid degradation. The hydrogels released gallic acid (GA) and ellagic acid (EA) in increasing amounts with higher SS content and promoted the attachment of osteoblast cells (MC3T3-E1) and fibroblast cells (NCTC clone 929) [118].

2. Collagen: Collagen, a natural protein with triple-helical fibrils, is instrumental in accelerating bone regeneration. One approach involved a bioactive collagen nanohydroxyapatite (nHA) scaffold designed for bone repair. This scaffold enabled the localized delivery of BMP2 and vascular endothelial growth factor (pVEGF) using a non-viral dual delivery system. The scaffold showed substantial therapeutic efficacy in promoting bone regeneration, with complete bridging of defects observed in rats after four weeks, highlighting its potential for enhancing bone healing [119].

3. Gelatin: Gelatin, derived from the partial hydrolysis of collagen, has shown promise in drug delivery systems. Raina et al. developed a macroporous composite biomaterial consisting of gelatin, hydroxyapatite (HA), and calcium sulfate for co-delivery of bone morphogenic protein-2 (rhBMP2) and zoledronic acid (ZA). This biomaterial, which mimics trabecular bone structure, improved osteoconductivity and induced osteogenic differentiation in MC3T3-E1 cells. In vitro studies showed controlled release of rhBMP2 and ZA, with approximately 65% of rhBMP2 released over four weeks in vivo. This system demonstrated the potential for reducing the dosage of both rhBMP2 and ZA while maintaining effective delivery and bone regeneration [120]. Protein-based green nanotechnologies offer innovative and effective solutions for treating bone disorders by utilizing natural proteins for drug delivery and tissue engineering. These approaches not only enhance the functionality of biomaterials but also align with sustainable practices in nanotechnology.

4.3. Calcium-Based Green Nanotechnologies

Calcium phosphate (CP), a natural bone mineral, is an important component of green nanotechnologies for managing bone disorders and developing drug delivery systems. Here are notable examples of calcium-based approaches:

1. CP-Coated Cells: Gonzalez-McQuire et al. developed a method for preparing CP-coated human mesenchymal stem cells (MSCs) using bio-functionalized hydroxyapatite (HA) colloids. This technique promoted osteoblastic differentiation without the need for external growth factors and enhanced gene transfection rates in osteosarcoma cells and primary bone marrow stromal cells. The CP-coated MSCs acted as living biocomposites, demonstrating effective cell activity and potential for cryopreservation and lineage development [121].

2. DNA-Loaded Calcium Phosphate Nanoparticles: Yang et al. utilized DNA-loaded calcium phosphate (CP) nanoparticles to protect DNA from external DNase and release it in a low-acid environment. This approach effectively promoted odontogenic differentiation of rat dental pulp stem cells cultured in 3D scaffolds, demonstrating the potential of CP-NPs as non-viral gene delivery vectors for BMP2 transfection and odontogenic differentiation [122].

3. Iron-Doped Hydroxyapatite Nanoparticles: A study revealed that doping hydroxyapatite nanoparticles with 10% iron (Fe) enhanced their antibacterial properties, biocompatibility, and bioactivity. These Fe-doped HA nanoparticles allowed for controlled and sustained drug release, offering a promising material for bone repair, particularly for osteoporosis, where targeted calcium delivery is crucial [123].

4.4. Silica-Based Green Nanotechnologies

Silica-based ordered mesoporous materials have emerged as innovative carriers for drug delivery and bone regeneration. These materials can be loaded with various molecules and release them in a controlled manner. Notably:

1. E-Selectin Thioaptamer Ligand Conjugated Silica Nanoparticles: Mann et al. developed a multifunctional drug delivery system using biocompatible porous silicon nanoparticles conjugated with an E-selectin thioaptamer ligand (ESTA). This system served as a delivery platform for imaging agents and growth factors like colony-stimulating factor (CSF), protecting bone marrow from chemotherapy and radiation [127].

2. Mesoporous Silica with Controlled Release: Ordered mesoporous silica was synthesized using a surfactant-assisted sol-gel process, allowing for the controlled release of metronidazole, an antibiotic and antiprotozoal drug. The material demonstrated potential as both a drug carrier and bone substitute, showing promise for bone disease applications [128].

3. Mesoporous Silicate Nanoparticles in 3D Scaffolds: Yao et al. developed mesoporous silicate nanoparticles incorporated into a 3D nanofibrous gelatin scaffold for dual delivery of BMP2 and deferoxamine (DFO). DFO is a hypoxia-mimetic drug that triggers angiogenesis, while BMP2 promotes osteogenesis. The scaffold effectively controlled the release of both drugs, supporting bone tissue applications through their combined angiogenic and osteogenic effects [129].

Conclusion

The exploration of drug delivery systems for osteogenic disorders through the lens of green nanotechnology presents a promising paradigm shift in treating bone diseases. Traditional drug delivery approaches often grapple with challenges such as inadequate targeting, systemic toxicity, and limited efficacy in addressing bone disorders. Green nanotechnology, characterized by its use of sustainable and environmentally friendly methods for nanomaterial synthesis, offers a compelling alternative to these conventional systems. Green nanotechnology enhances drug delivery by utilizing nanomaterials (NMs) that can navigate biological barriers more efficiently than larger particles, thus improving drug targeting and minimizing systemic side effects. Polysaccharide-based systems, such as those employing heparin and chitosan, have shown considerable promise in enhancing drug release and promoting bone regeneration. Protein-based approaches,

including those utilizing silk sericin and collagen, leverage natural materials to support bone repair and tissue engineering. Calcium-based systems, exemplified by DNA-loaded calcium phosphate nanoparticles, provide innovative solutions for gene delivery and targeted osteoblast differentiation. Additionally, silica-based technologies enable controlled release and multifunctional applications, further advancing the field of bone disorder treatment. Despite these advancements, several challenges remain. The production of NMs via green methods must ensure high biocompatibility and avoid toxic by-products, and the efficiency of drug targeting and controlled release requires further refinement. Future research should aim to address these issues by optimizing green nanotechnology-based systems and validating their effectiveness through rigorous clinical trials. In summary, green nanotechnology represents a significant step forward in the development of drug delivery systems for osteogenic disorders. Its potential to enhance drug targeting, reduce toxicity, and promote bone regeneration aligns with the growing need for sustainable and effective treatments in the field of bone health.

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أنظمة توصيل الأدوية للاضطرابات العظمية باستخدام تكنولوجيا النانو الصديقة للبيئة

الملخص:

الخلفية: النظام الهيكلي، الذي يعدّ أساسياً للدعم الهيكلي والحركة والعمليات الأيضية المختلفة، يتم إعادة تشكيله باستمرار من خلال النشاط المتوازن للأوستيو بلاستيس والأوستيو سايتس والأوستيو كلاستس. تؤدي الاضطرابات في هذا التوازن إلى اضطرابات العظام، بما في ذلك هشاشة العظام وعظام العظام غير الطبيعية، مما يتطلب استراتيجيات علاجية فعالة. تواجه أنظمة توصيل الأدوية التقليدية تحديات مثل ضعف كفاءة الاستهداف والتسمم الجهازي.

الهدف: تستعرض هذه المراجعة تطبيق تكنولوجيا النانو الصديقة للبيئة في تطوير أنظمة توصيل الأدوية المتقدمة لعلاج الاضطرابات العظمية. تركز تكنولوجيا النانو الصديقة للبيئة على استخدام طرق صديقة للبيئة لتصنيع المواد النانوية (NMs) التي تعزز توصيل الأدوية وتعزز تجديد العظام مع تقليل التسمم.

الطرق: تقيم المراجعة أنظمة توصيل الأدوية المعتمدة على تكنولوجيا النانو المختلفة، بما في ذلك البيسفوسفونات والنتراسيكلينات والأوليغوببتيدات والأبتاميرات، وتطبيقاتها في صحة العظام. تسلط الضوء على قيود الأساليب التقليدية وإمكانات تكنولوجيا النانو الصديقة للبيئة لتجاوز هذه التحديات. تشمل المراجعة تكنولوجيا النانو الصديقة للبيئة القائمة على السكريات المتعددة، والبروتينات، والكالسيوم، والسيليكا وأدوارها في تحسين توصيل الأدوية للاضطرابات العظمية.

النتائج: أظهرت تكنولوجيا النانو الصديقة للبيئة وعداً كبيراً في تعزيز توصيل الأدوية للاضطرابات العظمية. توفر الأنظمة القائمة على السكريات المتعددة، مثل مجمعات الهيبارين والكيروزان، قدرات محسنة للاستهداف وإطلاق الأدوية. تدعم التقنيات القائمة على البروتينات، بما في ذلك السلك السيريسين والكولاجين، إصلاح العظام وتجديدها. تظهر الأنظمة القائمة على الكالسيوم، مثل الجسيمات النانوية للفوسفات الكالسيوم المحملة بالحمض النووي، إمكانات في توصيل الجينات وتمايز الأوستيو بلاستيس. توفر الأنظمة القائمة على السيليكا إطلاقاً محكماً للأدوية وتطبيقات متعددة الوظائف.

الاستنتاج: تقدم تكنولوجيا النانو الصديقة للبيئة نهجاً تحويلياً لتوصيل الأدوية للاضطرابات العظمية، معالجاً قيود الأنظمة التقليدية. من خلال استخدام طرق تصنيع صديقة للبيئة وتعزيز الاستهداف وإطلاق الأدوية، تمتلك تكنولوجيا النانو الصديقة للبيئة القدرة على تغيير استراتيجيات العلاج للاضطرابات العظمية. يجب أن تركز الأبحاث المستقبلية على تحسين هذه التقنيات وتوسيع تطبيقاتها السريرية لتحسين نتائج المرضى.

الكلمات المفتاحية: تكنولوجيا النانو الصديقة للبيئة، أنظمة توصيل الأدوية، الاضطرابات العظمية، المواد النانوية، تجديد العظام، التصنيع الصديق للبيئة.