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Applications of Hydroxyapatite in Healthcare Sectors – A Perspective Review

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Abstract

Nano-hydroxyapatite (nHAp) provides a promising prospect in the field of healthcare owing to its biocompatibility and resemblance to the mineral composition of genuine bone. Nevertheless, there are still obstacles to overcome in order to convert its potential into practical applications. An important challenge is to develop scalable and reproducible synthesis methods that guarantee constant quality of nano-hydroxyapatite (nHAp). Ensuring precise control over particle size, shape, and purity is of utmost importance, as these parameters have a direct influence on the biocompatibility and effectiveness. Furthermore, it is necessary to conduct further research on the long-term stability and degradation rates in living organisms in order to ensure proper absorption of materials and minimize the risk of toxicity. Notwithstanding these difficulties, nHAp exhibits great potential. The capacity to function as a precise drug delivery system, namely for the treatment of bone disorders and cancer, is a highly intriguing field of study. Moreover, scaffolds built on nHAp exhibit promise in the field of bone tissue engineering and regenerative medicine. By integrating antibacterial compounds or altering the surface features of nHAp, there are possibilities for addressing infections and inflammation. Maximizing the complete capabilities of nHAp requires continuous research, namely in the areas of scalable synthesis, toxicity assessment, and clinical application. Successfully overcoming these obstacles will clear the path for nHAp to completely transform the healthcare industry and contribute to a new age of patient care.

Keywords: Hydroxyapatite; Healthcare; Bone; Dentistry

1 Introduction

Hydroxyapatite is an inherent calcium phosphate mineral that closely resembles the mineral constituent of bones and teeth [1]. Hydroxyapatite (HAp) innate biocompatibility renders it a highly sought-after substance in diverse therapeutic domains. The widespread usage of this material in various medical and dental applications is due to its distinct characteristics, such as bioactivity, biocompatibility, and osteoconductivity.[2] The significance of HAp in healthcare lies in its capacity to stimulate bone development and regeneration. HAp serves as a scaffold in orthopaedic applications, promoting the growth of fresh bone tissue. Furthermore, the capacity of HAp to directly adhere to bone renders it a highly suitable substance for implants and coatings, guaranteeing their enduring durability and seamless integration with the body[3].

This review will examine the various applications of HAp in the field of healthcare, including its utilization in bone tissue engineering, dental care, drug delivery systems, wound healing, cancer treatment, and antimicrobial applications. In addition, we will examine the biocompatibility and probable toxicity of HAp, along with the difficulties and future prospects of this adaptable biomaterial.

2 Synthesis and characterization of nanohydroxyapatite (nHAp)

Hydroxyapatite can be produced using many techniques, such as wet chemical precipitation, hydrothermal treatment, and sol-gel processing[2,4]. The selection of the synthesis technique often relies on the intended characteristics of the HAp, including factors like particle size, shape, and level of crystallinity. Furthermore, HAp can undergo functionalization with diverse materials to augment its characteristics and broaden its range of uses. For example, HAp can be integrated with polymers to produce composites that possess enhanced mechanical characteristics. Additionally, HAp can be altered with pharmaceuticals or bioactive substances to provide regulated administration of medications[3].

The nHAp is the nanoscale version of hydroxyapatite, has gained considerable interest in recent times because of its exceptional bioactivity, large surface area, and similarity to the natural apatite present in bones and teeth. The references cited are Pushpalatha et al., 2023 and Mazumder et al., 2019[1,5]. Precise control over the size, morphology, and crystallinity of nHAp is essential for its effective utilization in diverse domains including as biomedicine, dentistry, and environmental remediation.

2.1 Methods of synthesis

Several techniques have been devised for the production of nHAp, each possessing its own benefits and constraints. Several often utilized techniques include:

The wet precipitation method is a commonly employed technique that entails the interaction of calcium and phosphate precursors in a solution containing water. Although it is a straightforward and economical approach, achieving precise control over particle size and morphology can present difficulties[6].

The Sol-Gel Method is a highly adaptable technique that enables precise manipulation of particle size and morphology through the utilization of metal alkoxides as precursors. The sol-gel technique encompasses hydrolysis and condensation reactions, resulting in the creation of a gel that may be further manipulated to produce nHAp[7].

Hydrothermal synthesis is a technique that uses elevated pressure and temperature to facilitate the creation of crystalline nHAp. It enables the creation of well-formed nanoparticles with a specific shape and structure[8].

Microwave-Assisted synthesis refers expedited and energy-efficient technique employs microwave radiation to hasten the rate of chemical reactions, leading to reduced synthesis durations and diminished particle dimensions[9].

Biomimetic synthesis refers to a method that imitates the natural processes of bone formation. It involves employing biomolecules or simulated body fluids to regulate the nucleation and development of nHAp[10].

2.2 Methods for characterization

It is essential to characterize the synthesized nHAp in order to determine its appropriateness for certain applications. Several methodologies are utilized to ascertain the physicochemical characteristics of the substance, which encompass:

X-ray diffraction is a method that yields data on the crystal structure, phase purity, and crystallinity of nHAp[11]. Fourier Transform Infrared Spectroscopy (FTIR) is a technique used to determine the chemical composition of nHAp by identifying its functional groups. This method, as described by Balasubramanian and Mahalaxmi (2024)[12], confirms the presence of specific chemical groups in nHAp. Transmission Electron Microscopy (TEM) is a technique that allows for the visualization of nHAp at a high level of detail. It gives high-resolution images that provide important information on the size, shape, and distribution of nHAp particles[13]. Scanning Electron Microscopy (SEM) provides a comprehensive examination of the surface structure and analysis of particle size for nHAp[14]. Dynamic Light Scattering (DLS) is a technique used to determine the hydrodynamic size and size distribution of nano Hydroxyapatite (nHAp) particles in a liquid medium[15].

2.3 Factors affecting nHAp synthesis

Various factors can impact the characteristics of synthesized nano-hydroxyapatite (nHAp), such as: the parameters that affect the reaction are temperature, pH, reaction duration, and precursor concentrations. These parameters are important in influencing the size, shape, and structure of the particles formed during the reaction[16]. The selection of calcium and phosphate precursors can impact both the rate at which the reaction occurs and the characteristics of the end product[17]. The addition of surfactants, chelating agents, and other additives can alter the surface characteristics, size, and structure of nHAp [18].

3 Nanohydroxyapatite in bone tissue engineering

The objective of bone tissue engineering is to restore and rejuvenate impaired or diseased bone tissue, thereby enhancing the quality of life for numerous individuals afflicted with bone abnormalities resulting from trauma, infection, or illness. The nHAp is a highly promising material in this sector because of its exceptional biocompatibility, bioactivity, and osteoconductivity. It closely resembles the composition and structure of genuine bone mineral. The references cited are Abere et al. (2022), Noor (2013), and Fu et al. (2021) [19–21]. The nHAp, a scaffold material, mimics the structure of natural bone apatite. It serves as a framework for cell adhesion, proliferation, and differentiation, according to Munir et al. (2022) [22]. The research has demonstrated that nHAp scaffolds have the ability to improve the attachment, growth, and specialization of osteoblasts, which are cells responsible for bone production. This ultimately results in the creation of new bone [19]. The nanoscale characteristics of nHAp offer an expanded surface area that enhances protein adsorption and cellular interactions, hence facilitating the process of bone rebuilding.

The nHAp has exceptional biocompatibility, its mechanical characteristics, specifically its brittleness, may restrict its use in load-bearing bone defects. The references cited are Munir et al. (2022) and Tsai et al. (2018) [22,23]. In order to address this constraint, researchers have investigated the integration of nHAp into several composite materials. The mechanical strength and toughness of the scaffolds can be enhanced by incorporating nHAp with polymers like as chitosan, collagen, and polylactic acid, without compromising their biocompatibility [24,25]. nHAp can function as a transporter for bioactive compounds, including growth factors and medicines, to promote bone repair. [26] The porous nature of nHAp scaffolds enables the absorption and gradual release of these substances, which stimulates the growth, specialization, and creation of blood vessels at the site of injury.

3.1 The role of nanohydroxyapatite in bone regeneration

Orthopaedic medicine continues to face a substantial obstacle in the form of bone regeneration, necessitating the development of efficient treatments to repair bone abnormalities resulting from trauma, disease, or surgery [19,27]. The nHAp has gained attention as a potential biomaterial for bone regeneration due to its close resemblance to the mineral component found in normal bone [19,28]. This review explores the diverse function of nHAp in enhancing the process of bone regeneration, based on recent research discoveries. The chemical composition and crystal structure of nHAp closely mimic those of real bone apatite, making it biocompatible and osteoconductive [10,19,22]. It is biomimicry enables it to effortlessly integrate with the host bone tissue, creating an optimal environment for bone cell adhesion, proliferation, and differentiation [19,22,29,30].

The nHAp can be manufactured into porous scaffolds with interconnected pores that replicate the structure of real bone [25,31]. The scaffolds serve as a three-dimensional structure that allows cells to adhere, migrate, and build new bone [32]. The small dimensions of nHAp increase its surface area, facilitating the attachment of proteins and the contact between cells and the substance, which is essential for bone regeneration. The research has shown that nHAp has the ability to promote the transformation of mesenchymal stem cells into osteoblasts, which are the cells responsible for creating new bone tissue [33]. The ability of nHAp to activate certain signaling pathways involved in osteogenesis is responsible for its osteoinductive function. The effective bone regeneration necessitates the creation of fresh blood vessels (angiogenesis) to provide oxygen and nutrients to the developing tissue. Studies indicate that nHAp has the ability to enhance angiogenesis by triggering the secretion of angiogenic growth factors [34].

3.2 Scaffolds and composites

Bone tissue engineering aims to overcome the constraints of existing bone grafting methods by creating biocompatible alternatives that replicate the structure and functionality of natural bone. Hydroxyapatite, a ceramic composed of calcium phosphate that closely resembles the mineral found in bones, has become a prominent choice for creating scaffolds for bone construction [35]. This review explores the existing literature on scaffolds and composites based on Hydroxyapatite (HAp), emphasizing their characteristics, manufacturing techniques, and uses in bone regeneration.

Porous hydroxyapatite (HAp) scaffolds serve as a three-dimensional structure that facilitates the attachment, growth, and specialization of cells, hence promoting the production of new bone [26]. An optimal HAp scaffold should include interconnected pores that are of suitable size and distribution in order to promote cell migration, nutrition transport, and vascularization. Nevertheless, the inherent fragility of HAp restricts its use in bone abnormalities that need carrying heavy loads [36].

HAp Composites: In order to address the mechanical constraints of pure HAp scaffolds, scientists have investigated the combination of HAp with different biocompatible substances to produce composites that possess improved mechanical characteristics and biological functionality. The addition of Hydroxyapatite (HAp) to polymer matrices, such as polylactic acid, polyglycolic acid, and their copolymers, might enhance the mechanical strength, toughness, and processability of the scaffolds. The polymer component serves to give structural support, whilst HAp increases bioactivity and osteoconductivity[37].

Collagen, which is the predominant protein found in the extracellular matrix of bone, serves as a natural framework for the regeneration of bone[38]. The combination of hydroxyapatite (HAp) with collagen can improve the attachment, growth, and specialization of cells, hence facilitating the development of new bone tissue[5]. Bioactive glasses, renowned for their capacity to adhere to bone, can be integrated into HAp scaffolds to augment bioactivity and osteoconductivity[39]. These composite materials have demonstrated encouraging outcomes in facilitating the growth of new bone tissue and improving the connection between implants and surrounding bone.

3.3 Fabrication techniques

Several fabrication methods have been used to produce scaffolds and composites made of HAp, allowing for customization of their properties. These procedures include:

Porogen leaching is a process that includes combining HAp powder with a porogenic chemical, which is then removed to produce pores in the scaffold[23]. Freeze-drying, also known as lyophilization, is a process that involves the conversion of a frozen solvent directly into a gas, bypassing the liquid phase. This results in the formation of porous structures[40]. Electrospinning is a method that creates nanofibrous scaffolds characterized by a large surface area and linked holes, which closely resemble the structure of the natural extracellular matrix[41]. 3D Printing is the fast-advancing technology enables the accurate creation of intricate scaffold structures with controlled pore design[42].

4 Hhydroxyapatite in dentistry

HAp, due to its striking resemblance to the mineral composition of natural bone and teeth, has become a versatile biomaterial in the field of dentistry. The extensive utilization of this material in diverse dental applications is due to its biocompatibility, osteoconductivity, and capacity to stimulate tissue regeneration. HAp is a vital component in implant dentistry since it significantly improves the process of osseointegration for dental implants. Implants covered with hydroxyapatite (HAp) provide enhanced bone-to-implant contact and increased stability in comparison to implants without coating, as reported by Karamian et al. (2014)[43]. The improved osseointegration results in increased rates of implant success, decreased risk of implant loosening, and greater long-term outcomes for patients[44,45].

Periodontal regeneration involves the use of HAp in several forms such as granules, pastes, and membranes[44]. The osteoconductive qualities of this substance facilitate the development of new bone and the attachment of the periodontal ligament, hence aiding in the regeneration of periodontal tissues that have been lost[19]. Research has demonstrated that materials containing HAp can successfully decrease the depth of gum pockets, boost the level of connection between the gum and tooth, and promote the regeneration of gum tissue in individuals with periodontitis[1]. HAp is commonly employed in operations to enhance the alveolar ridge. This helps to correct insufficient alveolar ridges, making it easier to install dental implants or enhance the durability of dentures[46]. HAp-based bone graft substitutes serve as a framework for the development of new bone, improving the size and strength of the alveolar ridge. This enhances the visual appeal and operational effectiveness of dental prostheses[47].

Dentin hypersensitivity is commonly treated using dentifrices and dental care products that contain HAp[48]. Nano-HAp's small particle size enables it to block exposed dentinal tubules, hence limiting fluid flow and relieving sensitivity[49] (Pei et al., 2019). Enamel remineralization is promoted by including Hydroxyapatite (HAp), a crucial element of tooth enamel, into oral care products. According to Okada and Furuzono (2012)[3], formulations of HAp that contain fluoride improve the process of remineralization and reinforce the enamel, providing protection against dental cavities.

5 Nanohydroxyaptite in drug delivery system

The nHAp has gained considerable interest as a potential material for drug delivery applications due to its excellent biocompatibility, bioactivity, and similarity to the mineral component of bone[5,19,50]. This review explores the existing literature on the utilization of nHAp in drug delivery systems, emphasizing its benefits, drawbacks, and recent progress. Its exhibits excellent biocompatibility and biodegradability, indicating that it does not cause any negative responses in the body and can be gradually decomposed and assimilated over a period of time[22,51]. The feature of nHAp makes it an appealing material for the development of secure and efficient medication delivery systems[19].

The small size of nHAp particles leads to a large surface area and porosity, allowing for efficient drug loading and regulated release[51]. It demonstrates an inherent attraction to bone tissue, rendering it highly appropriate for precise administration of drugs to bone cells and tissues. This focused strategy can improve the effectiveness of therapy while reducing the occurrence of unintended effects[51,52]. The surface of nHAp can be readily changed with different functional groups, enabling the conjugation of specific medicines or targeting ligands. The ability to adapt allows for the creation of tailored drug delivery systems to address specific therapeutic requirements[51].

5.1 Applications of nHAp in drug delivery

Bone illnesses, such as osteoporosis, osteomyelitis, and bone cancer, have been thoroughly investigated for the use of nHAp as a drug delivery system[51]. Due to its capacity to specifically target bone tissue and stimulate bone regeneration, it is an optimal vehicle for medicines that enhance bone development or hinder bone resorption[22].

The use of nHAp nanoparticles allows for the targeted delivery of chemotherapeutic drugs to tumour locations, resulting in a decrease in overall toxicity and an enhancement in treatment efficacy[19,22]. The nHAp has demonstrated potential as a vehicle for antibiotics, namely in the management of bone infections. The capacity to specifically target bacteria in bone tissue can augment the efficacy of antibiotics while reducing harm to healthy tissues[53]. The nHAp nanoparticles have been investigated as vehicles for gene therapy, transporting therapeutic genes to specific cells[29].

6 Hydroxyaptite's role in wound healing and soft tissue applications

Hydroxyapatite is primarily recognized for its ability to regenerate bones, but it is also gaining attention for its potential in wound healing and treating soft tissues. This review examines the current body of literature that investigates the possible advantages and drawbacks of HAp in various areas. The HAp's biocompatibility is essential for soft tissue applications, as it helps to minimize adverse reactions and promote integration with the body, similar to its role in bone[3]. The HAp's porosity structure serves as a scaffold for cell adhesion, proliferation, and migration, which are crucial activities in wound healing and tissue regeneration[33].

The research indicates that HAp, especially in its nanoscale form, may possess antibacterial capabilities, which might potentially decrease the likelihood of infection in wounds[54]. Presently, ongoing investigations and practical uses: wound dressings containing HAp have demonstrated promise in accelerating healing, diminishing inflammation, and improving tissue regeneration in animal models, as reported by Vivcharenko et al. (2021)[55]. The research is currently investigating the potential of HAp-based scaffolds as temporary skin substitutes for the treatment of burns and chronic wounds. These scaffolds serve as a framework for the creation of new tissue[56]. The potential of HAp to serve as a medication carrier is now being studied for targeted administration of antibacterial drugs or growth factors to enhance wound healing[23].

7 Applications of nHAp in cancer treatment

The nHAp, commonly used in bone regeneration, is now being considered as a potential treatment for cancer due to its distinct characteristics. This study examines the existing research that investigates the many uses of nHAp in fighting cancer.

7.1 Mechanism of actions

The anticancer benefits of nHAp are ascribed to a multitude of pathways, which encompass: the research has demonstrated that nHAp has the ability to trigger apoptosis, which is a process of programmed cell death, in many types of cancer cells such as prostate, breast, and glioma cells[51,52,57,58]. The ability of nHAp to regulate intracellular signaling pathways that control cell survival and apoptosis is responsible for this impact.

The nHAp has been shown to possess the capacity to impede the proliferation and migration of cancer cells, so successfully reducing the growth of tumours and their spread to other parts of the body[57,59]. As previously mentioned, the characteristics of nHAp can be utilized to transport chemotherapeutic drugs directly to tumour locations, enhancing the effectiveness of treatment and minimizing damage throughout the body[60].

8 Antimicrobial properties

The HAp, a calcium phosphate ceramic known for its ability to interact well with living tissue and its likeness to the mineral found in bones, has gained attention for its potential to fight against microorganisms and germs. This comprehensive review examines the current body of literature, investigating the mechanisms, uses, and future prospects of HAp in fighting against microbial diseases.

The HAp, surfaces can possess a positive charge, which has the ability to attract bacterial cell walls that are negatively charged. This attraction can lead to the disruption of the integrity of the bacterial cell walls[61]. This interaction has the potential to cause membrane damage, resulting in the release of cellular contents and, ultimately, the death of bacteria. It has the ability to release calcium (Ca^{2+}) and phosphate (PO^{43-}) ions. These ions can hinder bacterial metabolism and disturb crucial cellular processes[62,63]. Elevated levels of these ions can have a harmful effect on bacteria.

Certain studies indicate that HAp, especially in its nanoform, has the ability to produce reactive oxygen species such as hydroxyl radicals (• OH) under specific conditions[64]. These extremely reactive compounds have the ability to harm bacterial DNA, proteins, and lipids, resulting in the death of the cell. The HAp has synergistic effects when combined with antibacterial drugs, such as antibiotics or silver ions, resulting in an enhanced efficacy of these medicines. The observed synergistic impact can be ascribed to three factors: enhanced medication delivery, heightened local concentration of antibacterial drugs, or increased bacterial sensitivity[65–67].

8.1 Applications of antibacetrial Hap

*8.1.1 **Orthopaedic implants and bone regeneration***

The intrinsic biocompatibility and osteoconductivity of HAp make it a widely used material for orthopaedic implants and bone grafts. Integrating antibacterial qualities into these materials might effectively mitigate implant-associated infections, which are a significant problem in orthopaedic surgery. Coating metallic implants with hydroxyapatite (HAp) that is infused with antibacterial chemicals such as silver or copper ions has demonstrated encouraging outcomes in diminishing bacterial adhesion and the production of biofilms[68]. HAp scaffolds that include antibiotics have the ability to carry drugs directly to the infected area, which improves the eradication of bacteria and facilitates the rebuilding of bone tissue[69].

*8.1.2 **Uses in Dentistry***

HAp is extensively utilized in the field of dentistry for a range of purposes, such as dental implants, bone grafting materials, and restorative composites. The antibacterial characteristics of this substance can be advantageous in the prevention of tooth caries and periodontal disorders. Incorporating HAp nanoparticles that are doped with antibacterial agents into dental composites has the potential to hinder bacterial development and decrease the likelihood of secondary caries, as demonstrated by Erdem et al. (2020)[14]. Applying antibacterial HAp coatings to dental implants can effectively inhibit bacterial colonization and minimize the likelihood of peri-implantitis, as demonstrated by Erdem et al. (2020)[14].

*8.1.3 **Wound healing***

The biocompatibility, porosity, and possible antibacterial characteristics of HAp render it a highly promising material for applications such as wound dressings and tissue engineering scaffolds. The HAp is a beneficial component in wound dressings since it facilitates wound healing by creating a moist environment, absorbing exudate, and potentially preventing bacterial growth[2,70]. HAp scaffolds, made from hydroxyapatite, have the potential to serve as temporary skin substitutes in the treatment of burns and chronic wounds. The inclusion of antibacterial medicines in these scaffolds can effectively inhibit infection and facilitate tissue regeneration[71].

9 Biocompatibility and toxicity

Hydroxyapatite is a calcium phosphate ceramic that closely resembles the mineral component of bone. It is well-known for its ability to be compatible with living tissues and its ability to promote bone growth. These characteristics have resulted in its widespread utilization in diverse biomedical applications, including as orthopaedic implants, dental materials, and drug delivery systems. This review examines the current body of literature on the biocompatibility and potential toxicity of HAp, investigating how it interacts with biological systems and addressing any relevant problems. The high biocompatibility of HAp is derived from its chemical resemblance to the mineral found in genuine bone. After being implanted, HAp demonstrates exceptional integration with nearby tissues, resulting in a low immune response and facilitating the formation of new bone.

9.1 Key factors contributing to HAp's biocompatibility

The chemical makeup of HAp consists mostly of calcium and phosphate ions, which closely resemble the composition of natural bone mineral. This similarity enables HAp to integrate smoothly with surrounding tissues and reduces the occurrence of foreign body reactions[72]. Surface features of Hydroxyapatite (HAp), such as its electrical charge, roughness, and porosity, have a significant impact on cell adhesion, proliferation, and differentiation. These factors eventually affect tissue regeneration, as demonstrated by[19,23]. HAp has a low solubility in physiological settings, which means it remains stable for a long time. Nevertheless, it has the capability to experience gradual deterioration, resulting in the release of calcium and phosphate ions that can have a positive impact on bone restructuring[72].

9.2 Potential toxicity of hydroxyapatite

Although HAp is generally regarded as biocompatible, there are several conditions that can affect its potential toxicity. The research has demonstrated that nano-sized HAp particles can elicit distinct biological reactions in comparison to bigger particles, as indicated by studies conducted by Mazumder et al. in 2019[5]. The enhanced surface area of nanoparticles can result in increased cellular contact and potentially trigger cytotoxicity[73].

Impurities and doping agents in HAp, which are typically introduced during synthesis or processing, can modify its biocompatibility[73,74]. It is essential to guarantee the integrity and meticulously assess the biological impacts of any additives. The biocompatibility of HAp can also be affected by the location where it is implanted and the amount that is administered. Exposure to large concentrations of HAp nanoparticles throughout the body may cause concerns regarding potential toxicity to organs such as the liver and kidneys[73,75].

10 Challeges and future perspectives

The nHAp shows great potential in many healthcare fields such as orthopaedics, dentistry, and drug delivery, and it has exceptional biocompatibility, bioactivity, and similarity to genuine bone mineral. Nevertheless, there are still numerous obstacles and subjects for further investigation that need to be addressed in order to fully unlock its potential.

10.1 Challenges

Obtaining a significant amount of nHAp with uniform size, shape, and crystal structure is still a difficult task[3]. Existing synthesis techniques sometimes suffer from a lack of repeatability, which hampers the ability to scale up laboratory achievements to industrial manufacturing. Having precise control over the size, shape, surface charge, and porosity of nHAp is essential for customising its performance in specific applications. It is crucial to develop strong synthesis techniques that enable precise adjustment of these features.

Although nHAp is typically compatible with living organisms, additional research is needed to understand its long-term stability and how it breaks down in the body. Comprehending and managing the rate at which degradation occurs is essential for guaranteeing proper absorption of materials and preventing any potential negative consequences. The enhanced surface area and reactivity of nanoparticles give rise to concerns regarding possible toxicity, especially when exposed for extended periods. Comprehensive toxicological investigations are essential for evaluating the safety of nano-hydroxyapatite (nHAp) in different applications and doses.

In order to transform encouraging outcomes obtained from laboratory experiments and animal studies into commercially feasible goods, it is necessary to conduct thorough testing, obtain regulatory permission, and carefully evaluate cost-effectiveness[76]. It is essential to tackle these issues in order to achieve general acceptance of therapies based on nHAp.

10.2 Prospects for the future

Drug delivery systems that are designed to specifically target and deliver medication to a particular area or cell in the body. The regulated drug delivery capabilities of nHAp make it well-suited for targeted administration of medications, especially in the treatment of bone disorders and cancer. Investigations into the surface modification and drug release mechanisms that respond to stimuli show significant potential. Nanohydroxyapatite (nHAp)-based scaffolds, when paired with growth factors and stem cells, present promising opportunities for the regeneration and repair of bone tissue. Creating biomimetic scaffolds that replicate the structure of the natural bone extracellular matrix is a primary area of concentration.

The effectiveness of nHAp in fighting infections and lowering inflammation can be improved by adding antibacterial agents or altering its surface characteristics. nHAp's customisable qualities make it well-suited for personalised medicine techniques, in which materials are engineered to meet individual patient requirements[77]. The integration of nHAp with other nanomaterials and technologies creates new opportunities in the fields of diagnostics and treatments. It is essential to investigate ecologically friendly and sustainable synthesis methods for nHAp in order to reduce environmental impact and advance green nanotechnology.

11 Conclusion

Synthesized nano-hydroxyapatite (nHAp) exemplifies the intersection of material science and medicine, providing a flexible framework for tackling a wide range of healthcare obstacles. The intrinsic biocompatibility, osteoconductivity, and ability to distribute drugs in a customized manner have sparked a significant increase in research and development, generating confidence for its potential to bring about transformation. Nevertheless, the journey from the laboratory bench to the patient's bedside is filled with obstacles. It is crucial to develop synthesis methods that can produce nHAp with uniform physicochemical properties, while also being scalable and reproducible. To address issues regarding the long-term stability, control of degradation, and potential nanotoxicity, it is necessary to conduct thorough investigations and develop creative solutions. Moreover, it is crucial to navigate the intricate aspects of clinical translation, regulatory obstacles, and cost-effectiveness considerations in order to fully achieve the clinical benefits of nHAp-based medicines.

Notwithstanding these difficulties, the prospects for synthesized nHAp in healthcare are highly promising. The extensive potential of targeted drug delivery systems, biomimetic scaffolds for bone tissue creation, and antibacterial/anti-inflammatory applications is highlighted by ongoing research. As we go further into the field of personalized medicine and nanomedicine, the capacity to customize the characteristics of nHAp to meet unique patient requirements presents extraordinary opportunities for diagnostics and therapies. Despite the remaining obstacles, synthesized nHAp possesses exceptional qualities and a wide range of uses, making it a leading force in healthcare innovation. Through ongoing research, interdisciplinary collaboration, and a resolute dedication to overcoming current obstacles, the use of nHAp has the potential to transform the field of medicine and introduce a new age of patient care.

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