Mini Review

Polymer Nanocomposites for Biomedical and Environmental Applications - a Mini-Review

Carmen Steluta Ciobanu, Simona Liliana Iconaru and Daniela Predoi*
National Institute of Materials Physics, Romania

Abstract
Polymer nanocomposites compounds (PNCs) are an emerging class of materials that integrate polymer matrices with nanoscale fillers (such as hydroxyapatite), in order to enhance their physico-chemical and biological properties. This mini-review present recent advances in PNCs development and their potential applications in biomedical and environmental domain. The focus of this mini-review is on how the incorporation of nanoparticles into the polymer matrix (dextran) tailors the performance and allows for use in multifunctional applications (such as: biomedical, environmental, etc.).

SHRINE PUBLISHERS
Crafting your Achievement

Shrine Journal of Research and Sciences (SJRS)

ISSN: 3069-2032

Volume 2 Issue 1, 2025

Article Information
Received date: September 29, 2025
Published date: October 13, 2025

***Corresponding author**
Daniela Predoi, National Institute of Materials Physics, Romania

DOI: 10.65070/SJRS.2025.810

Keywords
Hydroxyapatite; Osteoconductivity; Biomedical engineering; Environmental applications; Dextran matrix

Introduction

Polymer nanocomposites combine polymer matrices with nanoscale fillers, such as metal oxides, graphene, carbon nanotubes, and hydroxyapatite, leading to improved physicochemical and biological properties [1-12]. Hydroxyapatite (HAp), a calcium phosphate ceramic with the chemical formula $Ca_{10}(PO_4)_6(OH)_2$, is of particular interest to the scientific community due to its excellent biocompatibility and osteoconductivity, as its chemical similarity to the mineral component of bone allows it to promote bone regeneration [1,3]. HAp nanoparticles can be doped with various ions such as zinc, magnesium, or cerium to enhance their biological features [1,2]. To improve the properties of HAp nanoparticles, dextran - a biocompatible, water-soluble polysaccharide composed mainly of glucose units linked by α-1,6 glycosidic bonds - is often used as a matrix [1,3]. Dextran-coated nanoparticles exhibit improved dispersibility and stability, prevent aggregation, and promote cellular interactions, while facilitating controlled drug delivery [1,3]. These composite materials also exhibit enhanced antimicrobial and bioactive properties [1,3]. The incorporation of nanoparticles into the polymer matrix allows the development of composite materials with properties that are not possible to obtain with conventional polymers alone. Consequently, PNCs are widely used in the development of functional coatings, and environmental technologies [2,8]. Previous studies have highlighted that uses functional coatings could offer antimicrobial activity, corrosion resistance, UV protection, and stimuli-responsive behaviour [1-12]. The use of PNC in biomedical applications can optimize drug delivery, support tissue engineering, and facilitate the development of bioactive coatings that enhance cell proliferation while minimizing the risk of infections [3,7]. Environmental applications are a current research topic, and PNCs could be used to improve the adsorption capacity of pollutants, in water treatment, in air purification, etc. [6,12].

Synthesis and Properties of Polymer Nanocomposites Materials (Pncs)

Polymer nanocomposites combine polymer matrices with nanoscale fillers, such as metal oxides, graphene, carbon nanotubes, and hydroxyapatite, leading to improved physicochemical and biological properties [1-12]. Hydroxyapatite (HAp), a calcium phosphate ceramic with the chemical formula $Ca_{10}(PO_4)_6(OH)_2$, is of particular interest to the scientific community due to its excellent biocompatibility and osteoconductivity, as its chemical similarity to the mineral component of bone allows it to promote bone regeneration [1,3]. HAp nanoparticles can be doped with various ions such as zinc, magnesium, or cerium to enhance their biological features [1,2]. To improve the properties of HAp nanoparticles, dextran - a biocompatible, water-soluble polysaccharide composed mainly of glucose units linked by α-1,6 glycosidic bonds - is often used as a matrix [1,3]. Dextran-coated nanoparticles exhibit improved dispersibility and stability, prevent aggregation, and promote cellular interactions, while facilitating controlled drug delivery [1,3]. These composite materials also exhibit enhanced antimicrobial and bioactive properties [1,3]. The incorporation of nanoparticles into the polymer matrix allows the development of composite materials with properties that are not possible to obtain with conventional polymers alone. Consequently, PNCs are widely used in the development of functional coatings, and environmental technologies [2,8]. Previous studies have highlighted that uses functional coatings could offer antimicrobial activity, corrosion resistance, UV protection, and stimuli-responsive behaviour [1-12]. The use of PNC in biomedical applications can optimize drug delivery, support tissue engineering, and facilitate the development of bioactive coatings that enhance cell proliferation while minimizing the risk of infections [3,7]. Environmental applications are a current research topic, and PNCs could be used to improve the adsorption capacity of pollutants, in water treatment, in air purification, etc. [6,12].

Properties of Polymer - Nanocomposites Materials

Functionalization of doped HAp with dextran can confer several improvements of their properties. Mechanical properties, including tensile strength, Young's modulus, and toughness, are increased, fact that improve coatings durability [5,8]. Thermal stability is also enhanced, with nanoparticles increasing heat resistance and degradation temperatures, which is crucial for industrial and environmental applications [12,6]. In biomedical contexts, this type of materials could enhance osteoconductivity and reduce microbial growth, whereas in environmental contexts, nanocomposite membranes and adsorbents efficiently remove dyes, heavy metals, and organic pollutants from water and wastewater [1,7,6,12]. Therefore, optimizing nanoparticle concentration, and surface modification is critical to maximize these synergistic effects and achieve multifunctional performance [11]. The magnesium-doped hydroxyapatite in dextran matrix (10MgHApD) nanocomposite was thoroughly characterized using SEM, EDS, XRD, FTIR, and Minkowski Functionals to assess its physico-chemical properties [13]. SEM revealed agglomerated particles with spherical morphology, while EDS provided insights into the elemental composition. XRD confirmed the hexagonal crystalline structure of hydroxyapatite, and FTIR analysis demonstrated the presence of dextran within the composite [13]. Minkowski Functionals highlighted nonconventional yet high-quality surface patterns [13]. Together, these findings indicate that the nanocomposite possesses a well-defined structure, uniform morphology, and functional surface chemistry suitable for advanced biomedical applications [13]. The physico-chemical analysis of dextran-coated cerium-doped hydroxyapatite (CeHAp-D) thin films, deposited on silicon substrates via radio frequency magnetron sputtering, revealed smooth and homogeneous surface morphologies without granular structures [3]. SEM, AFM, and MM confirmed the uniformity of the coatings, while EDX and GDOES underlined the presence of the expected elemental composition [3]. FTIR spectroscopy identified characteristic vibrational modes ($\nu 1$, $\nu 3$, $\nu 4$) of phosphate groups from hydroxyapatite, along with signals specific to dextran, confirming successful integration of both components [3]. These findings demonstrate that the CeHAp-D coatings possess well-defined structural, compositional, and surface properties suitable for biomedical applications [3].

In the study reported by Ghegoiu, L. et al. [7] was developed dextran-coated zinc oxide nanoparticles with various zinc oxide concentrations and investigated from physico-chemical point of view using XRD, SEM, and BET analysis [7]. The structural characterization confirmed the formation of nanocomposites with homogeneous and uniform morphology, while porosity data supported their suitability for biological interactions [7]. The study demonstrated that zinc oxide coated with dextran can be synthesized using a simple and cost-effective method [7]. Preliminary physico-chemical characterization revealed that the samples possess a high degree of purity, as indicated by the absence of additional peaks in the XRD pattern [7]. The crystallinity of the samples was found to increase with higher zinc oxide concentrations, while the specific surface area measured by BET analysis increased as the zinc oxide concentration decreased [7]. These findings confirm that the structural and surface properties of the nanocomposites can be improved by adjusting the zinc oxide content [7].

Potential Applications of Polymer Nanocomposites

Polymer nanocomposites are extensively applied in coatings due to their improved properties. Magnesium- and cerium-doped hydroxyapatite nanocomposites inhibit microbial growth and reduce infection risks on medical surfaces [2,3]. Metal and oxide nanoparticle-based coatings enhance mechanical durability and chemical resistance, making them suitable for harsh environments [4,11]. Nanocomposite coatings can also be engineered to respond to environmental stimuli, such as temperature, pH, or mechanical stress, enabling smart self-healing surfaces [12,8]. In automotive and aerospace industries, lightweight, robust PNC coatings are used for panels, aircraft components, and electronic devices [5,6]. Environmental protective coatings (made from polymer nanocomposites) improve resistance to UV degradation, chemical pollutants, and environmental stress, extending the lifespan of materials in challenging conditions [6,12].

Biomedical applications of polymer nanocomposites

In biomedical applications, according to the preview studies polymer nanocomposites play a crucial role in tissue engineering, drug delivery, and infection control. Hydroxyapatite and bioactive glass nanoparticles incorporated into polymer matrices promote osteoconductivity and facilitate cellular proliferation, which is critical for development of bone scaffolds and implants [1,3]. Functionalized nanoparticles allow controlled and targeted drug delivery, improving therapeutic efficiency while minimizing side effects [7,12]. Nanocomposite coatings on medical devices could reduce infection risk and enhance implant longevity [2,3]. Additionally, materials based on graphene and metal oxide-based nanocomposites provide platforms for biosensors and imaging applications due to their electrical and optical properties [8,5]. Due to their unique properties such as biocompatibility and mechanical strength, polymer nanocomposites hold great promise as next-generation materials for biomedical engineering.

Dextran-coated zinc oxide nanoparticles were developed with varying zinc concentrations [7]. These nanocomposites were tested for antimicrobial activity and showed strong inhibitory effects against: Gram-positive bacteria: Staphylococcus aureus, Enterococcus faecalis, Bacillus subtilis; Gram-negative bacteria: Pseudomonas aeruginosa, Escherichia coli; Fungal strain: Candida albicans [7]. Their broad-spectrum antimicrobial performance makes them promising candidates for biomedical applications, particularly as antimicrobial agents [7]. The study highlights several key applications for fluoride-doped hydroxyapatite (HApF) and dextran-enhanced HApF-Dx thin films: these coatings are highly suitable for biomedical applications, particularly in the development of biocompatible devices [14]. Their ability to promote adhesion and proliferation of human fibroblast cells (HGF-1), along with their uniform, crack-free surface morphology, makes them ideal for implant coatings and tissue engineering scaffolds [14]. The enhanced biological activity observed with the dextran matrix also supports their use in dental applications, such as restorative materials or protective layers for oral treatments [14]. Overall, the films demonstrate strong potential for advanced medical and dental technologies, where surface biocompatibility and cellular interaction are critical [14]. Another study conducted on the dextran coated cerium doped hydroxyapatite (CeHAp-D) composite coatings [3], developed by radio frequency magnetron sputtering, demonstrated their excellent biological features. Both 5CeHAp-D and 10CeHAp-D samples were harmless to human gingival fibroblasts, confirming their biocompatibility [3]. The coatings promoted healthy cell adherence and morphology, indicating their suitability for medical applications [3]. These findings underscore the potential of CeHAp-D coatings in the development of high-performance biocomposites for use in biomedical devices and tissue-contact surfaces [3].

Environmental applications of polymer nanocomposites

Due to their unique properties, polymer nanocomposites have emerged as key materials for environmental remediation and sustainable development. Nanocomposite membranes have been developed for water purification, efficiently removing heavy metals, dyes, and organic pollutants through adsorption and size-exclusion mechanisms [6,12]. Graphene-based and metal oxide nanocomposites exhibit high surface areas and photocatalytic activity, enabling the degradation of persistent organic pollutants, including dyes, pesticides, and pharmaceuticals, under UV or visible light irradiation [6,8]. Biopolymer-based nanocomposites offer sustainable alternatives to traditional polymers, reducing environmental impact while maintaining mechanical performance, and are used in packaging, coatings, and construction materials [12]. In addition to water treatment, polymer nanocomposites could be used in air purification. Photocatalytic nanocomposite coatings can degrade volatile organic compounds and airborne pollutants, contributing to cleaner indoor and industrial environments [6]. Nanocomposites are also used in environmental sensors for monitoring heavy metals and toxins, leveraging their high surface area and tunable surface chemistry for selective detection [8]. Moreover, the durability and chemical resistance of nanocomposites allow their use in harsh environmental conditions, such as wastewater treatment plants and chemical processing facilities, where conventional materials would degrade [6]. Emerging research focuses on integrating biodegradable polymer matrices with nanoparticles to create environmentally friendly, sustainable nanocomposites that maintain performance while minimizing ecological impact [12]. Overall, polymer nanocomposites offer solutions that address both pollution control, resource efficiency, and sustainability.

A biogenic magnetic nanocomposite (HAP@DEX@MNP) was developed using hydroxyapatite from eggshell waste and dextran to remove the herbicide 2,4-D from water [6]. The material showed: high adsorption capacity: 217.39 µg/g at 25 °C; effective removal at pH 2, driven by electrostatic, hydrogen bonding, π-π, and van der Waals interactions; adsorption behaviour: fit both Langmuir and Freundlich models, indicating monolayer and multilayer adsorption; kinetics: followed pseudo-second-order model; thermal versatility: effective across various temperatures; regenerability: easily regenerated using 0.1 M NaOH, making it reusable and eco-friendly [6].

Their results indicate that this nanocomposite holds promise as a sustainable and efficient material for water purification applications [6]. On the other hand, in the study reported by

Kokilavani S. et al. [15] was reported a rapid and cost-effective colorimetric assay using Cu-sensitized Ag-dextran nanocomposites (NCs) for the detection of Hg^{2+} ions in aqueous samples. The NCs had a hydrodynamic diameter of 26 ± 1.4 nm and a zeta potential of −32.21 ± 3 mV [15]. Upon interaction with Hg^{2+}, the nanocomposite changed color from brownish yellow to colorless, with a strong linear correlation between absorbance at 408 nm and Hg^{2+} concentrations ranging from 20 nM to 100 nM [15]. A portable paper-strip sensor was also developed for real-time detection [15]. The NCs demonstrated high specificity, sensitivity, and stability across varying pH, salinity, and temperature conditions [15]. Additionally, they showed excellent photocatalytic degradation of methylene blue under visible light and antimicrobial activity against Bacillus subtilis and Escherichia coli, confirming their multifunctional potential in environmental monitoring and biomedical applications [15].

Conclusion

Polymer nanocomposites are versatile materials with superior properties that could be used in biomedical and environmental applications. Advances in synthesis, nanoparticle functionalization, and their characterization have enabled properties control. In environmental contexts, polymer nanocomposites demonstrate the ability to purify water, degrade pollutants, improve air quality, and provide sustainable material alternatives. Future research is expected to focus on environmentally friendly, biodegradable nanocomposites and multifunctional devices that combine durability, responsiveness, and sustainability. Hydroxyapatite-dextran (HAp-dextran) composites represent a promising class of biomaterials with significant potential in biomedical applications. Their combined properties - hydroxyapatite's bioactivity, osteoconductivity, and structural similarity to bone, along with dextran's biocompatibility, hydrophilicity, and functional versatility - enable the development of advanced coatings, scaffolds, and drug delivery systems. Studies have shown that HAp-dextran materials support cell adhesion, proliferation, and differentiation, making them ideal for dental implants, bone regeneration, and tissue engineering. Moreover, their ability to be doped with therapeutic agents or antimicrobial elements further enhances their clinical relevance. In conclusion, HAp-dextran composites represent a proper candidate for potential uses in next-generation biomedical devices, combining structural integrity with biological performance to meet the evolving demands of regenerative medicine and therapeutic delivery.

Author Contributions

All authors have read and agreed to the published version of the manuscript.

References

1. Predoi D, Iconaru SL, Predoi MV (2019) Dextran-coated zinc-doped hydroxyapatite for biomedical applications. Polymers 11(5): 886.

2. Iconaru SL, Predoi MV, Motelica HM, Predoi D, Buton N (2020) Dextran-thyme magnesium-doped hydroxyapatite composite antimicrobial coatings. Coatings 10(1): 57.

3. Ciobanu CS, Nica IC, Dinischiotu A, Iconaru SL, Chapon P, et al. (2022) Novel dextran coated cerium doped hydroxyapatite thin films. Polymers 14(9): 1826.

4. Hassan T, Salam A, Khan A, Khan SU, Khanzada H, et al. (2021) Functional nanocomposites and their potential applications: A review. Journal of Polymer Research 28(2): 36.

5. Lee SJ, Yoon SJ, Jeon IY (2022) Graphene/polymer nanocomposites: Preparation, mechanical properties, and application. Polymers 14(21): 4733.

6. Bhushan B, Kotnala S, Nayak A (2024) Biogenic magnetic nanocomposite of hydroxyapatite and dextran: synthesis, characterization, and enhanced removal of 2, 4-D from aqueous environment. Environmental Science and Pollution Research 31(27): 39331-39349.

7. Ghegoiu L, Predoi D, Iconaru SL, Ciobanu SC, Trusca R, et al. (2024) Development of Dextran Coated Zinc Oxide Nanoparticles with Antimicrobial Properties. Journal of Composites and Biodegradable Polymers 12: 1-6.

8. Zhang G, Zhen C, Yang J, Wang J, Wang S, et al. (2024) Recent advances of nanoparticles on bone tissue engineering and bone cells. Nanoscale Advances 6(8): 1957-1973.

9. Huang F, Shen Y, Xie A, Zhu J, Zhang C, et al. (2007) Study on synthesis and properties of hydroxyapatite nanorods and its complex containing biopolymer. Journal of materials science 42(20): 8599-8605.

10. Sharma S, Bose JCK (2024) Biomedical Applications of Dextran. Biopolymers for Biomedical Applications pp. 219-251.

11. Wan L, Cui B, Wang L (2024) A review on preparation raw materials, synthesis methods, and modifications of hydroxyapatite as well as their environmental applications. Sustainable Chemistry and Pharmacy 38: 101447.

12. Fiume E, Magnaterra G, Rahdar A, Verné E, Baino F (2021) Hydroxyapatite for biomedical applications: A short overview. Ceramics 4(4): 542-563.

13. Predoi D, Ciobanu SC, Iconaru SL, Ţălu Ş, Ghegoiu L, et al. (2024) New Physico-Chemical Analysis of Magnesium-Doped Hydroxyapatite in Dextran Matrix Nanocomposites. Polymers 16: 125.

14. Ghegoiu L, Predoi D, Iconaru SL, Ciobanu CS, Rokosz K, et al. (2025) Physicochemical and Preliminary Biological Properties of Thin Films Based on Fluoride-Doped Hydroxyapatite in a Dextran Matrix for Biomedical Applications. Coatings 15: 565.

15. Kokilavani S, Syed A, Thomas AM, Elgorban AM, Bahkali AH, et al. (2021) Development of multifunctional Cu sensitized Ag-dextran nanocomposite for selective and sensitive detection of mercury from environmental sample and evaluation of its photocatalytic and anti-microbial applications. Journal of Molecular Liquids 321: 114742.