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Multifaceted Properties Of Pr-Ha/Pla Co-Doped Nanohydroxyapatite Composite: Insights Into Thermal And Antioxidant Activity

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This study meticulously explores the synthesis and comprehensive characterization of Praseodymium and polylactic acid co-doped nanohydroxyapatite (Pr-HA/PLA) composites, focused on their thermal stability, mechanical reinforcement, and antioxidant efficacy. The composites demonstrated a significant enhancement in adhesion strength, registering a 22.70 MPa increase, and a notable improvement in Vickers microhardness, rising by 10 units to 332 Hv. Additionally, the antioxidant activity was measured at an impressive 89.2%. Structural analyses via FTIR confirmed the successful molecular interaction between PLA and Pr-HA, while XRD patterns indicated a phase transition from crystalline to amorphous structures, suggesting an altered material organization. Detailed morphological evaluations through FESEM-EDX and AFM revealed a maintained structural integrity with homogenous dispersion of the dopants. The thermogravimetric analysis further substantiated the material's superior thermal stability, enduring up to 300°C without significant degradation. Collectively, these attributes position Pr-HA/PLA composites as a high promise for cutting-edge biomedical applications, including bone tissue engineering, regenerative medicine, and targeted drug delivery, owing to their improved biocompatibility and robust antibacterial properties against Staphylococcus aureus, and Escherichia coli.

Keywords: Nanohydroxyapatite, Praseodymium, Polylactic acid, Antioxidant properties, Biomedical applications, Thermal stability.

INTRODUCTION

The extracellular matrix (ECM) of bone and dental tissues primarily comprises hydroxyapatite (HA), a mineral phase vital for mechanical strength and rigidity[1,2]. The arrangement of calcium phosphate crystals in HA maintains the integrity of the ECM, which is essential for load-bearing and deformation resistance. While HA provides rigidity, polymeric components contribute to elasticity and tensile strength. Hydroxyapatite scaffolds are extensively used in medical applications due to their ability to promote bone growth and interact effectively with biological components, supporting osteoconduction and osteogenic cell activities[3]. However, the brittleness and low tensile strength of HA restrict its application in load-bearing scenarios[4,5,6]. This limitation has spurred the development of composite materials that blend the bioactivity of ceramics with the mechanical properties of polymers. The affinity of HA for cell-binding proteins, coupled with its mechanical limitations, restricts its applications. The incorporation of biological elements into HA-based scaffolds aims to stimulate natural bone formation, albeit facing challenges such as poor drug solubility and a short lifespan[7,8]. Recent research has explored the incorporation of rare earth metals such as praseodymium (Pr) into HA scaffolds to enhance osteogenesis[9]. Praseodymium enhances physical properties and biological responses by engaging in cellular activities and immune functions[10,11]. Furthermore, polymer hydroxyapatite nanoparticles with rare earth metals exhibit antibacterial properties and are promising solutions for periodontal issues and dental prostheses[12,13]. Praseodymium-infused hydroxyapatite nanoparticles have been shown to be effective at controlling bacterial growth in bone wound dressings[14,15]. However, concerns arise regarding antibiotic resistance with the use of polylactic acid (PLA) as a carrier for medications or bioactive substances[16]. The objective of the present research is to establish a bio composite bone framework from praseodymium-doped hydroxyapatite and polylactic acid that has antibacterial properties and promotes cell growth[17,18]. The resulting Pr-doped HA/PLA bio composite scaffold shows promise for improving bone tissue engineering and regenerative medicine by offering enhanced biocompatibility, antibacterial properties, and cell proliferation support. Future research and in vivo studies are crucial for evaluating the efficacy, safety, and clinical potential of these materials, potentially advancing orthopaedic and dental treatments. This innovative approach aims to create an ideal bone scaffold that provides mechanical support and promotes new bone formation while preventing infections in medical applications.

EXPERIMENTAL

Synthesis

Praseodymium-doped hydroxyapatite (Pr-HA) nanoparticles were synthesized by first dissolving praseodymium salts and ammonium hydrogen phosphate in ethanol. This mixture was heated and stirred, followed by the addition of distilled water. Concurrently, calcium nitrate in the appropriate proportions was also dissolved in ethanol and stirred separately. The two solutions were then combined, allowed to react, and subsequently heated to achieve the desired [Ca+Pr]/P ratio of 1.67. The resulting nanoparticles were treated at 80°C for 6 hours. Next, the Pr-doped hydroxyapatite was incorporated into polylactic acid (PLA) to produce Pr-HA/PLA materials. This involved mixing the Pr-HA with PLA, forming gel mixtures that were then lyophilized after cross-linking with 0.5% glutaraldehyde, ensuring that the PLA concentration and pH remained constant. Mechanical and thermal evaluations of these composites revealed outstanding properties, including resistance to corrosion and chemical degradation, making them suitable for various industrial applications. A detailed characterization of their structural properties further underscores their potential uses. The successful synthesis and comprehensive characterization of praseodymium-doped hydroxyapatite (Pr-HA) nanoparticles, along with the development of PLA-coated biocomposites, represent significant advancements in the fields of biomedical and tissue engineering. These newly developed substances have encouraging qualities that point to a broad variety of possible uses. However, further in-depth analysis is essential to thoroughly assess their performance and determine their suitability for specific biomedical uses, including bone regeneration, drug delivery systems, and other tissue engineering applications.

Characterization

Praseodymium-polylactic acid/hydroxyapatite (Pr-HA/PLA) nanoparticles were comprehensively characterized using modern analytical methods. The combination of FTIR, XRD, FESEM-EDAX, and AFM provided comprehensive insights into the structural, morphological, and compositional characteristics of the synthesized nanoparticles. The mechanical testing revealed superior hardness and compressive strength, making these nanoparticles promising candidates for various advanced applications. Differential thermal analysis (DTA) was used to evaluate the thermal stability of these materials at high temperatures without degradation. Moreover, the bio-nanoparticles exhibited potent antioxidant and anti-inflammatory activities, in addition to effective antibacterial properties against various microorganisms. These multifaceted characteristics position Pr-HA/PLA composites as highly promising materials for the development of damaged bone scaffolds. The excellent biocompatibility, antibacterial activity, and mechanical properties demonstrated by these Pr-HA/PLA composites highlight their potential as versatile materials for bone tissue engineering applications.

Thermogravimetric Analysis (DTA)

Thermogravimetric analysis, widely used in materials science, was employed to evaluate the thermal behavior and stability of Pr-HA/PLA nanoparticles using a PerkinElmer Diamond DTA thermal analyzer in a nitrogen (N_2) atmosphere. The DTA results showed a significant enhancement in thermal stability of the nanoparticles across the 25-600°C range. The onset temperature of thermal degradation for Pr-HA/PLA was notably higher than that of pure PLA, indicating that HA nanoparticles delayed the decomposition process. Additionally, peak temperatures shifted to higher values, confirming improved thermal resistance. This enhancement is attributed to strong interfacial interactions between HA and PLA, highlighting the potential of Pr-HA/PLA nanoparticles for applications requiring high thermal stability.

Antioxidant Activity

The antioxidant properties of the Pr^{2+}/PLA-HA nanoparticles were evaluated in detail using a DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging antioxidant assay, following the protocol established by Brandt-Williams et al. This method provides a quantitative measure of antioxidant activity, underscoring the potential of these nanoparticles in applications aimed at reducing oxidative stress. The level of intensive cleaning was measured by the following DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging or antioxidant assay equation:

$$\text{DPPH antioxidant assay (\%)} = \left(\frac{A - B}{A}\right) \times 100$$

where A = Abs control and B = Abs sample

RESULTS AND DISCUSSION

Functional Group Identification and Analysis:

Figure 1 clearly shows the infrared absorption spectra for praseodymium-doped hydroxyapatite (Pr-HA), praseodymium-polylactic acid-codoped hydroxyapatite nanoparticles. These spectra show key peaks for phosphate group vibrations at 559 cm^{-1}, 731 cm^{-1}, 869 cm^{-1}, and 1087 cm^{-1}, and for OH, CH, CO, and in-plane OH stretching vibrations at 3589 cm^{-1}, 2941 cm^{-1}, 1671 cm^{-1}, 1019 cm^{-1}, 881 cm^{-1}, and 821 cm^{-1}. The presence of PLA is indicated by bands at 1671 cm^{-1} and 1019 cm^{-1}.The spectra of praseodymium and polylactic acid-codoped hydroxyapatite (HA- Pr/PLA) also display new peak bands at 564 cm^{-1}, 721 cm^{-1}, 871 cm^{-1}, and 1082 cm^{-1}, which correspond to phosphate stretching in Pr-HA with reduced intensity in the polymer mixture. The shift of the phosphate band from 1087 cm^{-1} in Pr-HA to 1076 cm^{-1} in praseodymium-polylactic acid-codoped hydroxyapatite suggests successful interactions between PLA and praseodymium-doped hydroxyapatite.

XRD structural characterization and analysis

Figure 2 shows the XRD structural characterization patterns for praseodymium-doped hydroxyapatite (Pr-HA), praseodymium-polylactic acid (PLA)-codoped hydroxyapatite (Pr-HA/PLA), and Pr-HA/PLA nanoparticles. The crystalline nature of praseodymium-doped hydroxyapatite (Pr-HA) was confirmed using the JCPDS card (09-0432) for apatite as a reference. In contrast, the XRD structural characterization of praseodymium-polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) indicated an amorphous polymer mixture. This was characterized by the absence of distinct crystalline peaks in the 2-theta range from 25° to 32°, suggesting an amorphous phase.

FESEM/EDX Investigation

Figure 3(a) shows the surface morphology of the praseodymium and polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticles, revealing a mix of smooth and porous regions due to the integration of Pr-HA into the PLA matrix. The high-resolution TEM images in Figure 3(b) show that the Pr-HA/PLA crystals form in nonparallel orientations relative to the HA lattice, indicating that structural disorder may influence the mechanical properties. Figure 3(c) displays the SAED pattern of the needle-shaped Pr-HA/PLA particles, which shows diffraction rings that confirm the presence of both crystalline and amorphous phases. These findings underscore the potential of Pr-HA/PLA composites in biomedical applications, offering a balance of mechanical strength and bioactivity.

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AFM Imaging Investigation

Figure 4 depicts the 3D surface textures of a) praseodymium hydroxyapatite (Pr-HA) and b) praseodymium-polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticles. Pr-HA exhibited a flat, smooth surface with minimal pits, indicating a uniform distribution. Conversely, Pr-HA/PLA displays an uneven surface with peaks and valleys, suggesting a heterogeneous material distribution and dispersed coatings. These surface characteristics hold significance for biomedical applications, potentially enhancing interactions with bodily fluids and facilitating accelerated degradation in simulated body fluid environments.

Mechanical characteristics and analysis

Figure 5 presents the mechanical characteristics of the developed materials:

a) Adhesion Strength: Figure 5(a) shows the evolution of the adhesion strength of the developed materials over time. The introduction of PLA to the Pr-HA material resulted in a significant increase in binding strength, reaching approximately 24.65 MPa in the composite coatings. This demonstrates the effectiveness of PLA in enhancing the adhesion between layers.

b) Vickers Microhardness (Hv): Figure 5(b) displays the Vickers microhardness test results, indicating a slight increase in hardness due to PLA incorporation. The Hv values were 322 for praseodymium-doped hydroxyapatite (Pr-HA) and 332 for praseodymium and polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticle samples.

These enhanced mechanical properties suggest the suitability of the Pr-HA/PLA composites for applications requiring high mechanical durability.

Antibacterial Properties

The antibacterial activity of the composites was investigated against the gram-positive pathogen Staphylococcus aureus and the gram-negative pathogen Escherichia coli. Materials coated with praseodymium and polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticles coated materials showed significant antibacterial effects across a concentration range of 50 to 80 µg/mL. Figures 6(a) and 6(b) illustrate that for praseodymium hydroxyapatite (Pr-HA) and praseodymium and polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticle-coated samples effectively inhibited the growth of both bacteria, with inhibition zones measuring 23 mm and 19 mm, respectively. The highest concentration of praseodymium-polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticles (80 µg/mL) exhibited the greatest antibacterial activity, indicating that the composite has potential as an alternative to conventional antibacterial agents. The integration of praseodymium ions and the structural benefits of hydroxyapatite and PLA renders these composites promising candidates for diverse biomedical applications, offering enhanced durability and infection control.
Figure 6a) and 6b) shows the results of antibacterial activity analysis
Antioxidant Activity
Pr-HA/PLA nanoparticles exhibit a remarkable set of properties that highlight their potential for a wide range of applications, particularly in biomedical and food packaging industries. The DPPH radical scavenging assay demonstrated an impressive antioxidant capability with

a scavenging efficacy of 89.2%, underscoring their ability to mitigate oxidative stress and extend the shelf life of perishable goods. Furthermore, the nanoparticles showcased exceptional thermal stability, with degradation occurring only at temperatures above 300°C, which indicates their suitability for applications requiring high durability and resistance to thermal stress.

The detailed structural, morphological, and compositional analysis of the Pr-HA/PLA composites confirmed their integrity and potential for advanced material applications. The research findings emphasize the composites' biocompatibility, antibacterial activity, and mechanical robustness, making them ideal candidates for the development of advanced bone tissue engineering scaffolds and other innovative biomedical products.

Overall, the multifaceted properties of Pr-HA/PLA nanoparticles make them promising materials for further exploration and utilization in various fields, particularly where durability, stability, and biocompatibility are critical.

In contrast, hydroxyapatite (HA) exhibited a substantially lower scavenging efficacy of 24.34%. Further examination revealed that the synthesized Pr/HA/PLA NPs exhibited antioxidant potentials ranging from approximately 70% to 82% at similar concentrations. However, this range was slightly lower than that of the Pr/HA/PLA NPs synthesized individually from these plants. The findings were consistent at a concentration of 100 µg/mL. Furthermore, at concentrations of 100 µg/mL and 50 µg/mL, the Pr-HA/PLA composites exhibited antioxidant activities of approximately 66% and 58%, respectively. This improvement in the surface activity of the dispersed nanoparticles highlights the superior antioxidant efficacy of Pr-HA/PLA. The slight decrease in activity, approximately 30%, observed in the Pr-HA/PLA composites can be attributed to their lower quantity, although their value remains comparable to that of Ag-doped hydroxyapatite Pr-HA/PLA. Furthermore, considering its physicochemical properties, antibacterial activity, and antioxidant activity, it is suggested that Pr/HA/PLA has potential for further advancements in biomedical technology.

Differential Thermal Analysis (DTA)

Figure 8 illustrate the differential thermal analysis (DTA) curves. Across the five compositions, the DTA plots showed minimal variations. Additionally, no distinct endothermic or exothermic peaks were detected in the DTA curves of the samples, suggesting their thermal stability between 25 and 1000 °C. Furthermore, the amount of dopant used in the study did not significantly impact the thermal stability of the apatite structure within this temperature range.

CONCLUSION

In this comprehensive analysis, composite of praseodymium-polylactic acid codoped in hydroxyapatite (Pr-HA/PLA) nanoparticles demonstrated good suitability for biomedical applications. The integration of polylactic acid in HA increased the binding strength and hardness, making the composite highly resilient to substantial loads and enhancing its stiffness. The biocompatibility, thermal stability, and antioxidative properties of these composites further broaden their potential for use in orthopaedic, dental, and regenerative medicine applications, offering promise for tissue integration, cellular interactions, and tissue regeneration. With its multifaceted advantages, the praseodymium-polylactic acid codoped in hydroxyapatite (Pr-HA/PLA) nanoparticle composite is a promising material in the field of biomedical engineering, and has the potential to address the complex requirements of clinical scenarios where durability, biocompatibility, antioxidant properties, and thermal stability are crucial.

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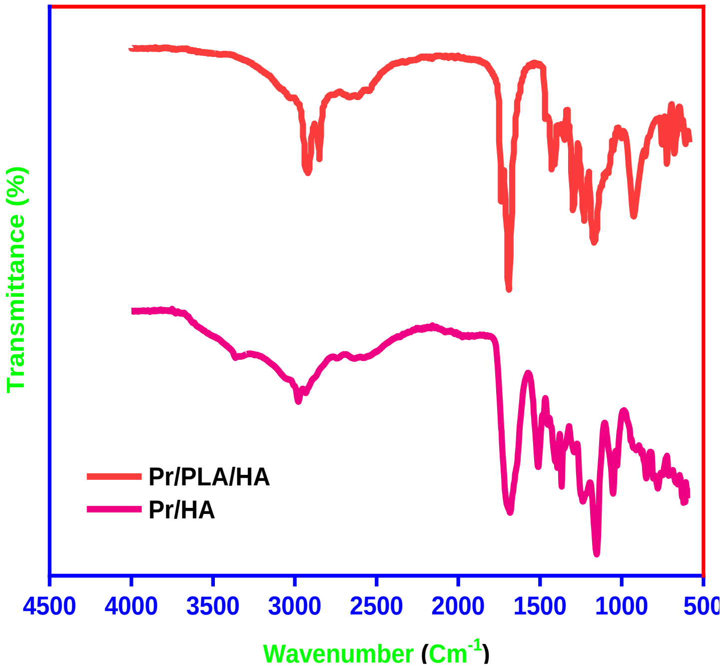
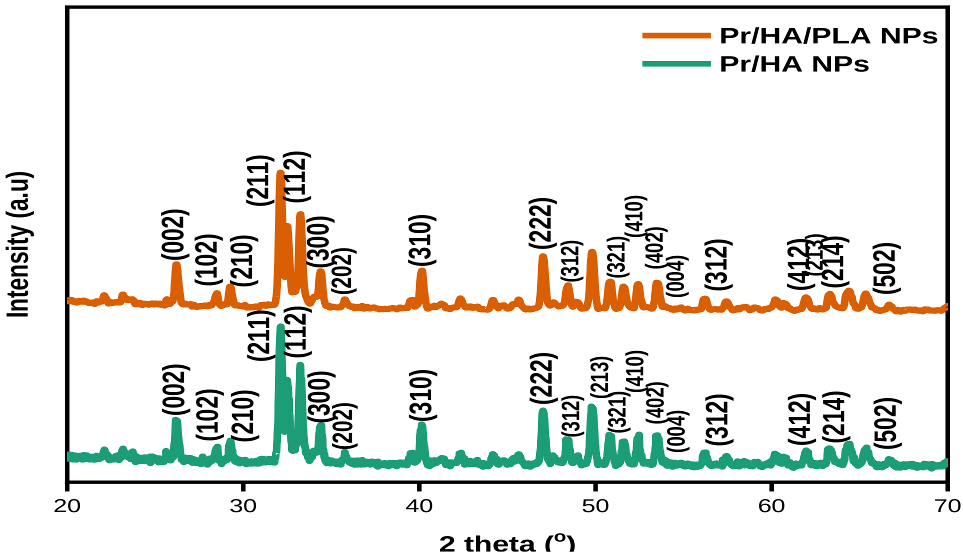


Figure 1) shows the FTIR spectra. Figure 2) shows the XRD pattern analysis.

FIGURE 1



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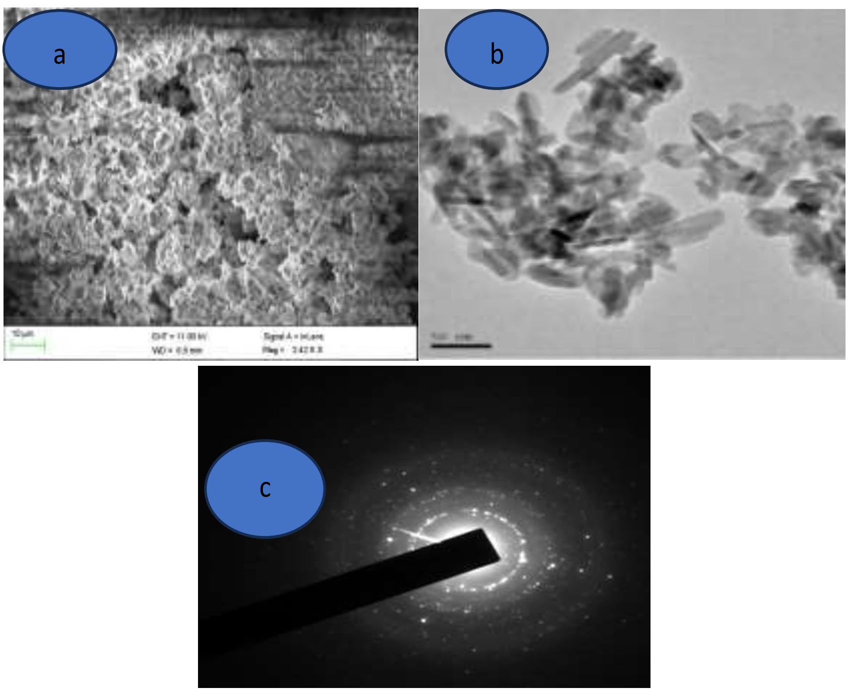


Figure 3 displays an investigation involving a) SEM, b) TEM, and c) SAED for the analysis of Pr-HA/PLA.

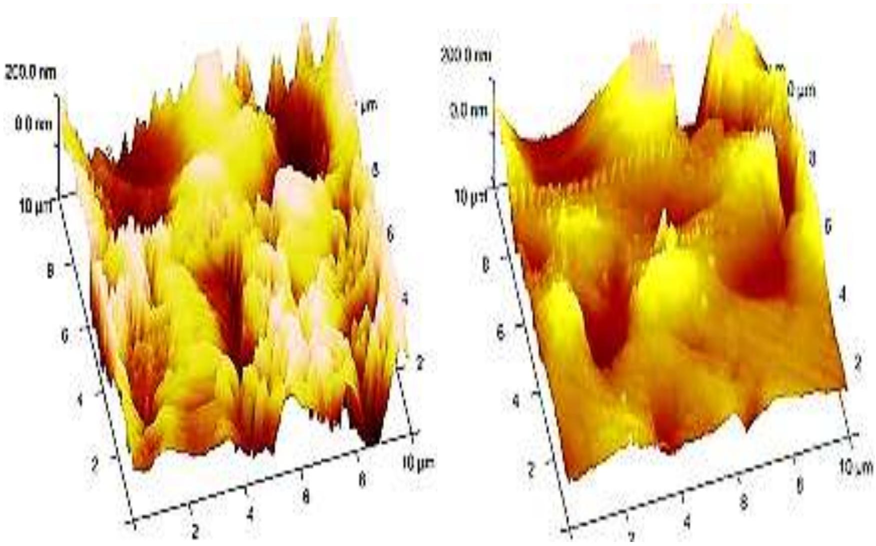
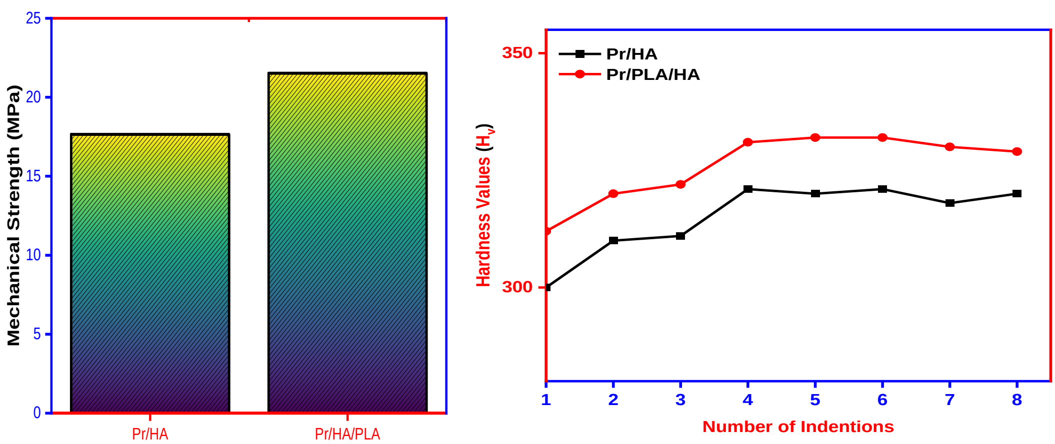


Figure 4). AFM analysis of a) praseodymium hydroxyapatite (Pr-HA) and b) praseodymium-polylactic acid-codoped hydroxyapatite (Pr-HA/PLA) nanoparticles



a) Pr-PLA b) HA-Pr/polylactic acid

Figure 5. a) Mechanical Characteristics and b) Hv Evaluation

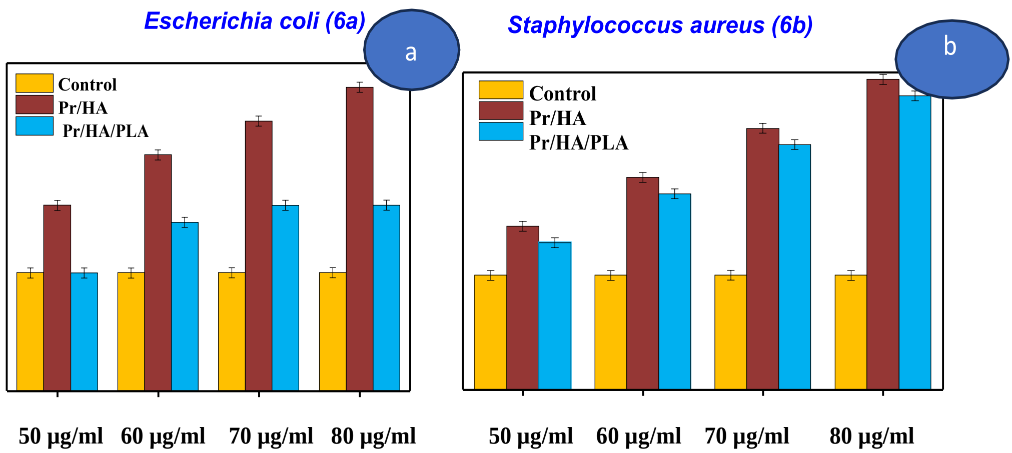


Figure 6a) and 6b) shows the results of antibacterial activity analysis

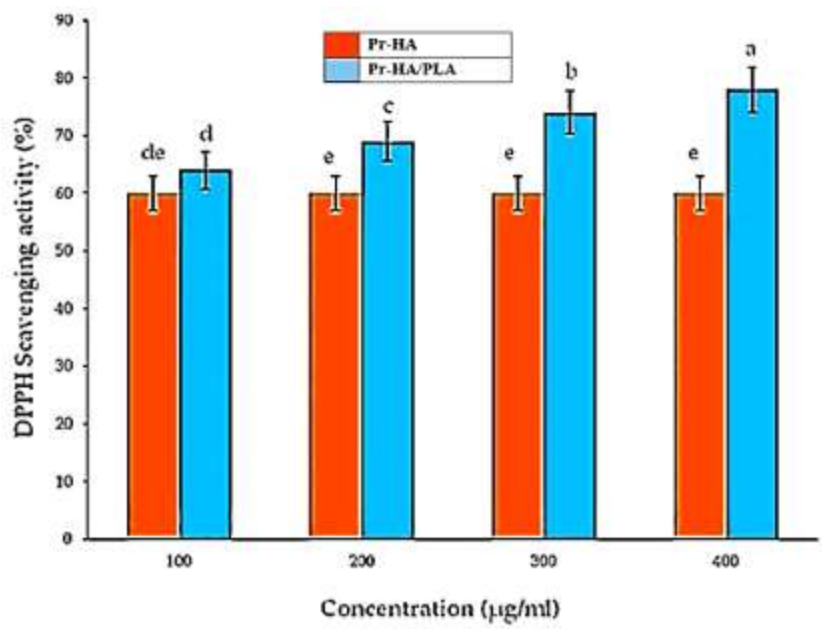


Figure 7 Antioxidant activities of Praseodymium hydroxyapatite (Pr-HA) and Praseodymium and polylactic acid codoped hydroxyapatite (Pr-HA/PLA) nanoparticles

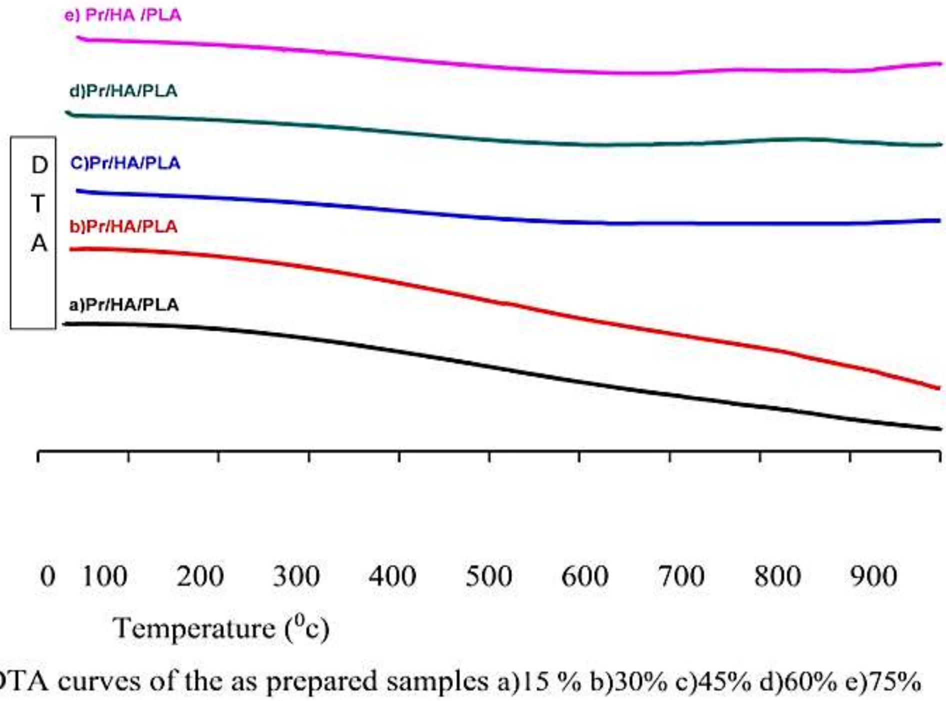


Figure 8 Differential thermal analysis (DTA) curves of Pr-HA/PLA