

A facile one-step preparation of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ /Li-BioMOFs resin nanocomposites with *Glycyrrhiza glabra* (licorice) root juice as green capping agent and mechanical properties study

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A facile one-step preparation of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ resin nanocomposites with *Glycyrrhiza glabra* (licorice) root juice as green capping agent and mechanical properties study

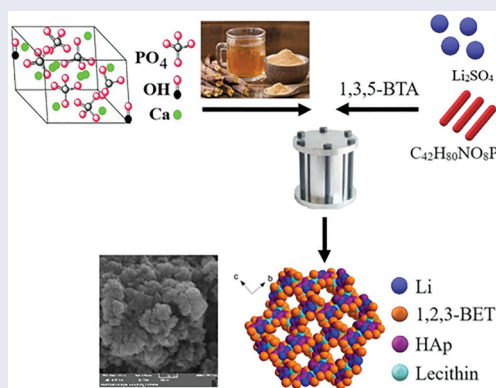
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ABSTRACT

The $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ resin nanocomposites were prepared and introduced as a new dental resin nanocomposite. $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ resin nanocomposites were synthesized with individual mechanical properties in the presence of lecithin as a biostabilizer. The hydrothermal synthesis of hydroxyapatite (HAp) nanostructures occurred in the presence of *Glycyrrhiza glabra* (liquorice) root juice that acts not only as a green capping agent but also as a reductant compound with a high steric hindrance agent. Results showed that the mechanical properties of nano- $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ structures with a concentration of 60 ppm Li-BioMOF were increased by ~ 132.5 MPa and 11.5 GPa for the flexural and Young's modulus, respectively. Based on the optical absorption ultraviolet-visible spectrum, the HAp nanocrystallites had a direct bandgap energy of 4.2 eV. The structural, morphological, and mechanical properties of the as-prepared nanoparticles were characterized with the FT-IR (Fourier-transform infra-red), UV-Vis (ultraviolet visible) spectrums, X-ray diffraction, SEM (scanning electron microscopy), and TEM (transmission electron microscopy) images, and atomic force microscopy (AFM). It is suggested that HAp structures loaded on the Li-BioMOFs are as a suitable and novel substrate which can be considered as a promising biomaterial in dental resin nanocomposites significantly improved the strength and modulus.

GRAPHICAL ABSTRACT



HIGHLIGHT

- For the first time $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-MOFs}$ were synthesised as dental resin nanocomposites with hydrothermal approach.
- *Glycyrrhiza glabra* (Liquorice) root juice acts not only as green capping agent but also act as reducing agent.
- Li-BioMOFs as a suitable substrate improve the hydroxyapatite mechanical properties.
- Li-BioMOFs substrates for $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ nanostructures were synthesised in the presence of lecithin as bio stabiliser.

Introduction

In the recent decades, nanostructures with a high potential in different domains have found application in medicine [1], optoelectronic devices [2], biological detection [3,4], drug delivery [5], biotechnology and biophysics [7,8], and dental nanocomposites [9,10]. Nanomaterials such as hydroxyapatites (HAPs), Ca compounds, $\text{SiO}_2/\text{TiO}_2$, poly biphenyl [11], and Ag nanocrystals are the main mineral components found in the bones have can have potential clinical applications due to their excellent biocompatible bioactive properties [12] and osteoconductivity [13]. Nano-hydroxyapatite with the chemical formula of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ is a substance rich of calcium and the major mineral material of bones and teeth, and serves as the main source of calcium [14–16]. In spite of many uses and advantages of HA, it has weaknesses in its mechanical properties, including breaking strength and fracture toughness [14,17,18]. There are many approaches such as reinforcing phases, added nanocomposites, and dense ceramic material are the best cases which can be used to improve its mechanical properties at biomedical applications [19–21]. HAP has a broad range of application in different fields, such as in tissue engineering [22,23], dentistry [24], fluorescent lamps [25], development of fuel cells [26], and orthopaedic

implants for bone replacement [27,28]. Based on nanotechnology, due to an increased surface-to-volume ratio in nanoparticles, nano-hybrid filling acts as a novel bioactive reinforcing filler with excellent bioactivity [29], biocompatibility [30], good wear resistance, decreased shrinkage, and unique mechanical properties [31]. Nano-HAP structures have been synthesized via various routes such as microwave-assisted synthesis [32], solvothermal [33], chemical precipitation [34], emulsion method [35], hydrolysis method [36], sol-gel method [37], and hydrothermal method [38]. Recently, nano-HAPs have been synthesised with different properties shown in Table 1. The hydrothermal method is a safe, cost-effective, mild, simple, practical [39], and environmentally friendly method compared to other methods that can be adopted to produce HAP nanocrystals. Recently, different plants extract as green capping agent and reductant have been widely used in the preparation of the nanostructures [40]. *Glycyrrhiza glabra* belongs to the Fabaceae family that has different phytochemicals such as glycyrrhizin, 18 β -glycyrrhetic acid, glabrin, and isoflavones [41]. Various extracts of this plant have a wide range of biological properties such as antibacterial, anti-inflammatory, antiviral, antidiabetic, and antioxidant [42]. Due to the more extensive applications of *Glycyrrhiza glabra* in green synthesis, in this study, NHA was prepared with *Glycyrrhiza glabra* (licorice) root juice through

Table 1. Summary of studies with different properties in recent years.

Types of Nanocomposites	Particle Size (nm)	Synthesis method	Application	References
Hydroxyapatite	15–50	biopolymer matrix	organic–inorganic composite	[46]
Fe@ hydroxyapatite	5–40	magnetic activation	bone regeneration	[47]
Ca/Sr/Ce/HAP	30–50	microwave	<i>in vitro</i> studies	[48]
Fe_2O_3 @HAP	25–40	Phase-Transfer Catalyst	synthesis of derivatives	[49]
Ce^{4+} /HAP	95–110	sol-gel refluxing	orthopaedic applications	[50]

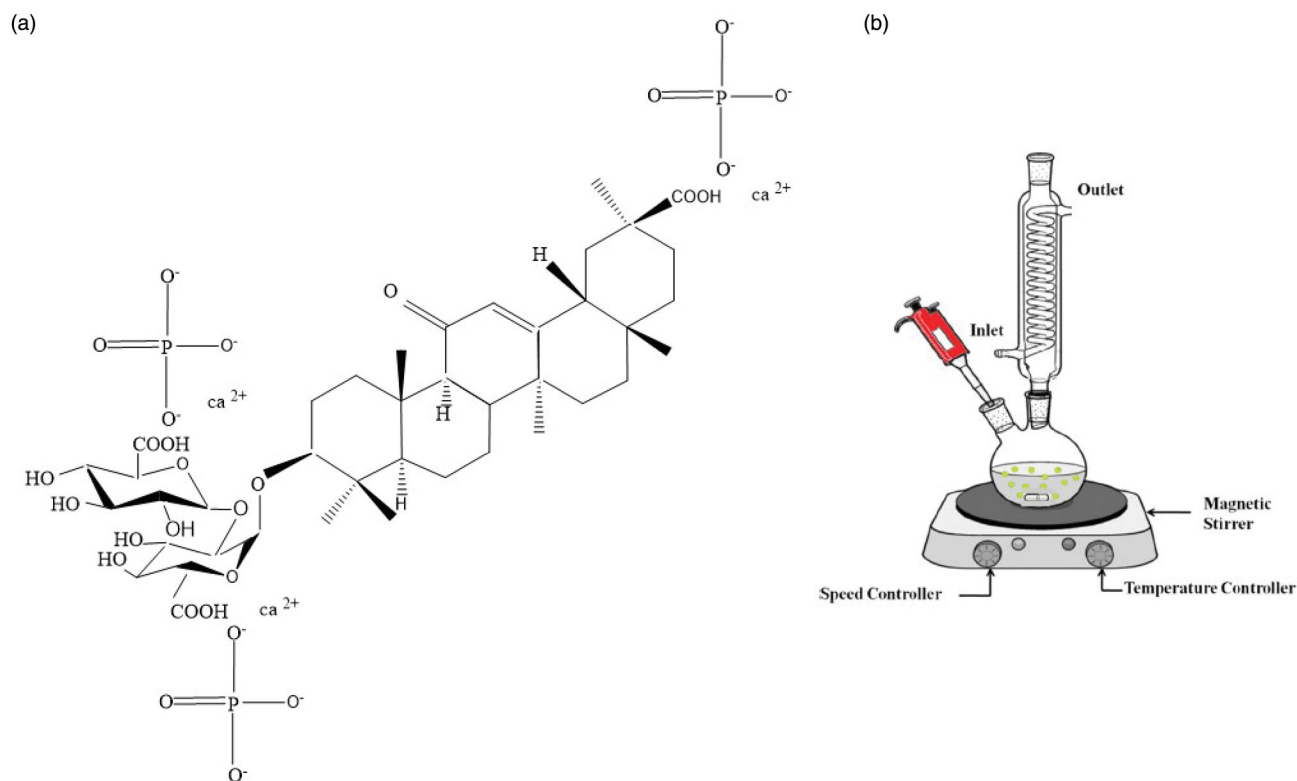


Figure 1. Proposed chemical structure of *Glycyrrhizic acid* (liquorice) root juice with HAP (a), experimental set up acquired the extraction of *Glycyrrhiza glabra* root juice (b).

Table 2. Reaction conditions for the preparation of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanostructure.

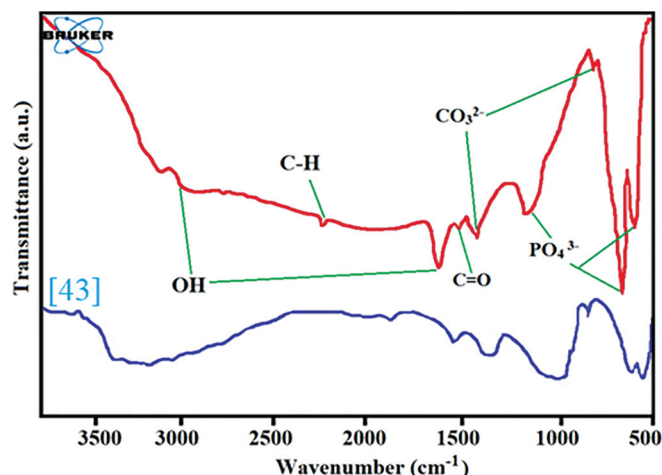
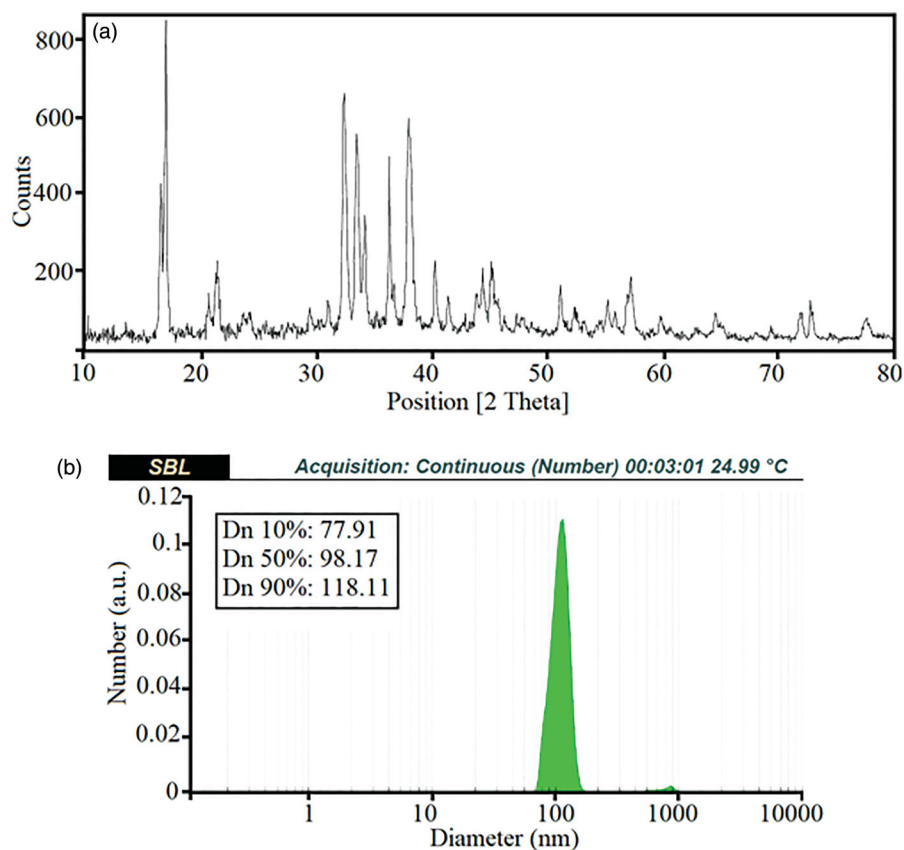
Sample	Li-BioMOFs (g)	pH	Time(min)	Temp. (°C)	Size (nm)
1	0.05	7.5–7.8	4	150	80–120
2	0.03	7.5–7.8	6	150	120–150
3	0.01	7.5–7.8	8	150	180–200
4	0.05	7.5–7.8	4	180	150–180
5	0.03	7.5–7.8	6	180	160–190
6	0.01	7.5–7.8	8	180	240–260
7	0.05	7.5–7.8	4	200	350–390
8	0.03	7.5–7.8	6	200	360–380
9	0.01	7.3–8.4	8	200	450–480

hydrothermal reaction for the first time, in which *Glycyrrhiza glabra* root juice acted as a crosslinking and auxiliary linker agent and a reductant compound and capping agent with high steric hindrance to produce NHA and Li-BioMOFs as a suitable and novel substrate. *Glycyrrhiza glabra* is one of the most important indigenous herbs in Iran, the main ingredient of which, i.e. glycyrrhizic acid ($\text{C}_{42}\text{H}_{62}\text{O}_{16}$), is shown in Figure 1(a). The synthesis of HAP nanoparticles was characterised by both mechanical and chemical properties with infra-red spectroscopy (FT-IR), ultraviolet spectroscopy (UV-vis), X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) images.

Experimental procedure

Materials and methods

All of the material, including NaOH, CaCO_3 (calcium carbonate, $\geq 99.0\%$), H_2PO_4 powder (96.986 g/mol Merck, reagent-grade), Li_2SO_4 (lithium sulphate, 99%, Sigma-Aldrich), cetyltrimethylammonium bromide (CTAB, Molar mass: 364.45 g/mol, $\geq 99.0\%$, Sigma-Aldrich), 1,3,5-benzenetricarboxylic acid (98%, Sigma-Aldrich), and lecithin as a bio emulsifier were used and received without further purification, purchased from Merck (Darmstadt, Germany). Also, deionised water was provided in the laboratory. The initial process of recrystallization yielded a yellow solution indicating the presence of impurities. Finally, a colourless solution was obtained indicating the purity of the material. XRD as a powerful analysis can be performed to examine nanomaterials' crystallography. The XRD patterns of the products were recorded

**Figure 2.** The FT-IR spectroscopy of the HAP nanostructures in range of 400–4000 cm^{-1} .**Figure 3.** The XRD patterns (a) and DLS diagram of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanostructures related to sample 1 (b).

with a Rigaku D-max C III, X-ray diffractometer using Ni-filtered Cu-K α radiation. To examine the morphological properties and particle size distribution, SEM images were obtained with Philips XL-30ESEM equipped with an energy dispersive X-ray spectroscopy (EDX) under the acceleration voltage of 100 kv. TEM images were obtained on a Philips EM208S with an accelerating voltage of 100 kV. The Fourier-transform infra-red spectroscopy (FT-IR spectra) were recorded by a Shimadzu Varian 4300 spectrophotometer in KBr pellets in the range of 400–4000 cm^{-1} . Atomic force microscopy (AFM) images were obtained with a Nano wizard II JPK Made (Germany).

Preparation of *Glycyrrhiza glabra* (liquorice) root juice extract

Since the root material of liquorice dissolves in water, the roots should be washed very quickly with running water.

After cleaning, the skin of the roots should be separated and then removed. The pieces were cut and dried for 10–15 cm. Then, the herbal dried roots were ground and the prepared powder was passed through a sieve with a specified mesh and extracted with water and ethanol (50 °C) for 6 h. The resulting solution was passed several times through a round-bottom double-neck flask to complete the extraction procedure. Figure 1(b) displays the experimental set-up for the extraction of *Glycyrrhiza glabra* root juice.

Preparation of nano-hydroxyapatite (nano-HAp)

In a typical method, 0.4 g of CaCO₃ was dissolved in 10 ml of distilled water; then, the pH of the prepared solution was adjusted to 7.5–8 using freshly prepared 1 M NaOH solution. The solution was placed on a heater for 120 min at 50 °C under constant stirring at 400 rpm. Then, 5 ml of *Glycyrrhiza glabra*

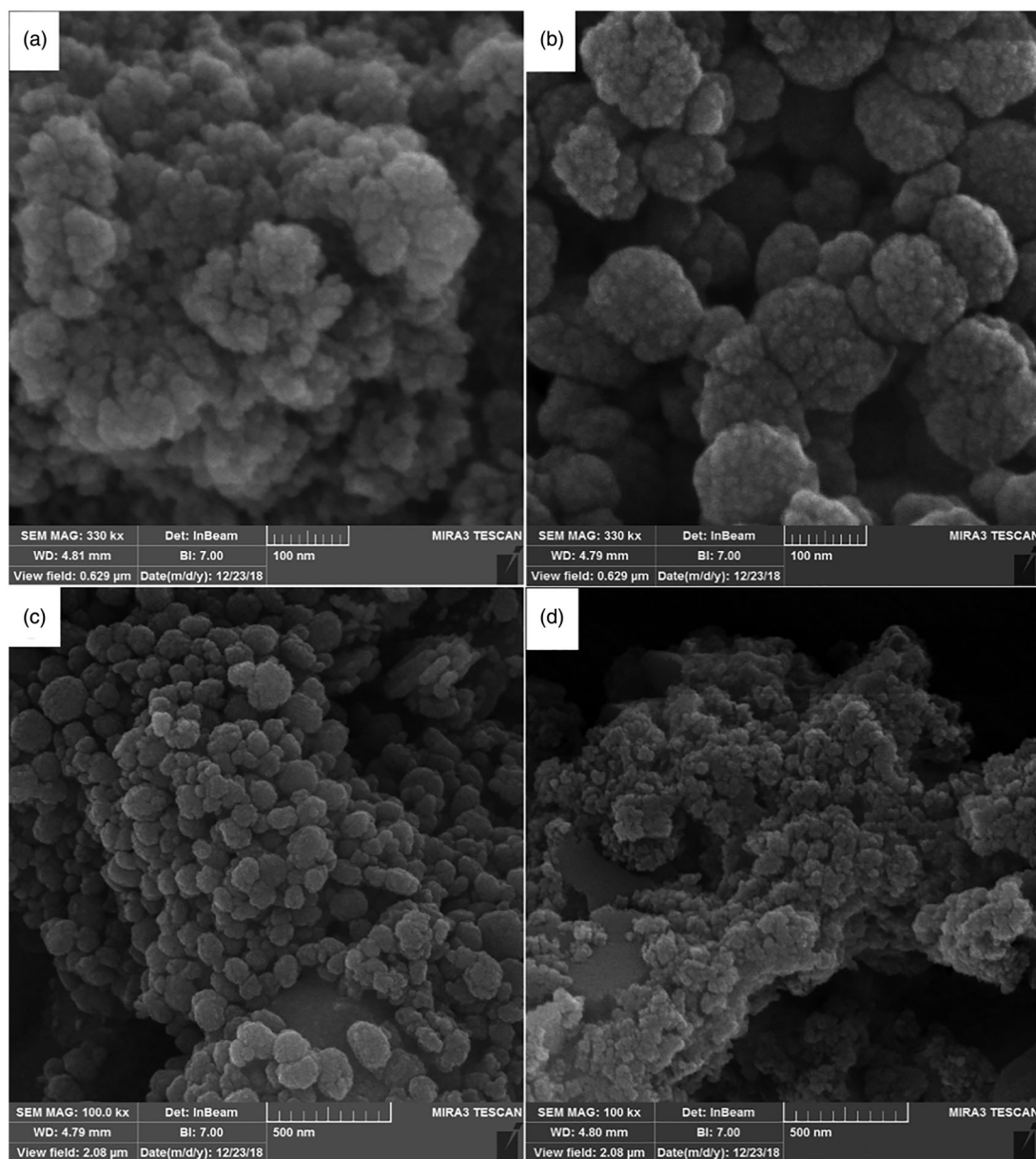


Figure 4. The SEM images of the Ca₁₀(PO₄)₆(OH)₂/Li-BioMOFs nanostructures prepared via hydrothermal method in condition of 150, 180 and 200 °C at 4 h (a–c) and SEM image of sample with co-precipitation method (d).

root juice was extracted and 0.5 g of H_2PO_4 powder (dissolved in 10 ml of distilled water) was added to the reaction mixture and placed in the oven for 2 days at room temperature. The products were eventually collected by filter paper, washed with ethanol, and dried at room temperature for 48 h.

Preparation of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$

Initially, 90 mg of Li_2SO_4 powder was dissolved in 20 ml of distilled water. Then, 0.05 g of CTAB was dissolved in 5 ml of 1:2 deionised water, and ethanol was gradually mixed with this solution and stirred at 400 rpm and 50°C until complete dissolution. Subsequently, 1 ml of lecithin 10% was poured dropwise into the reaction mixture for 30 min on a shaker. Next, 0.05 g of 1,3,5-benzenetricarboxylic acid was added to the above solution. Then, the reaction mixture was placed in an oven and heated for 12 h at 70°C . Finally, the synthesis materials were collected, washed with distilled water, and dried at 80°C for 24 h. To prepare the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$, 0.012 g of as-synthesized nano-HAp was added to a constant value of Li-BioMOFs as 0.01 g, 0.03 g, and 0.05 g, according to Table 2. The final products were characterized with FT-IR, UV-vis, XRD, SEM, TEM, and AFM.

Mechanical testing

Flexural strength tests were performed using the universal test machine at 5 mm/min crosshead speed. The flexural strengths of the nanocomposites were calculated by the following equation.

$$\sigma = 3 \cdot F \cdot L / 2 \cdot b \cdot d^2 \quad (1)$$

where σ (MPa) is flexural strength, F (N) is flexural load, L (mm) is span length, b (mm) is the width of the specimen, and d (mm) is the thickness of the specimen. To measure the strength tests, the stainless steel cylindrical moulds with a diameter of 4 mm and height of 6 mm were placed on a glass slide and then overfilled with the HAp nanocomposites; then, another glass slide was placed on the top of nanocomposites to compress the mould. All of the compressive strength tests were then performed with the universal testing machine at a cross-head speed of 1 mm min^{-1} .

Results and discussion

The FT-IR spectroscopy of the HAp nanocomposites was performed in the range of $400\text{--}4000 \text{ cm}^{-1}$ and the results are illustrated in Figure 2 and compared with natural polymers nanocomposites [43]. The absorption bands in the regions of 1630 cm^{-1} and 2950 cm^{-1} are related to OH^- stretching vibration in HAp structures. The presence of absorption peaks at $560\text{--}600 \text{ cm}^{-1}$ and $650\text{--}1300 \text{ cm}^{-1}$ is associated with PO_4^{3-} agents, justifying the presence of an HAp structure. The stretching band of P-OH appears at 3300 cm^{-1} and the absorption of C=O is shown at 1636 cm^{-1} . The absorption peaks at 835^{-1} and 1465 cm^{-1} can be attributed to the CO_3^{2-} group.

To characterise the phases, the crystallography and the examination of the crystallite size of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$,

XRD pattern analysis are shown in Figure 3(a). According to the X-ray pattern of HAp phases' nano-crystals[44], the presence of HAp phases' nano-crystals on the substrate Li-BioMOFs creates new peaks that could be due to the nanoparticles trapped in the network structure of the BioMOFs. The size distribution and the mean diameter of the crystallites, as well as the relationship between the wavelength of the X-ray beam and the distance between each set of atomic planes of the crystal lattice, were calculated at about 150 nm from the XRD peaks with the Debye-Scherrer equation [45] (Equation 2).

$$D = k\lambda / \beta \cos(\theta) \quad (2)$$

where D is the mean crystallites size, λ is the X-ray wavelength ($1.54 \text{ \AA}$), β is the broadening of the line measured at half its maximum intensity (in radius), θ is the diffraction angle from Bragg planes, and k is the shape factor. Dynamic light scattering (DLS) was adopted as a technique for measuring the size and intensity of particles, typically in the sub-micron and nanoscale region. The size of the final products

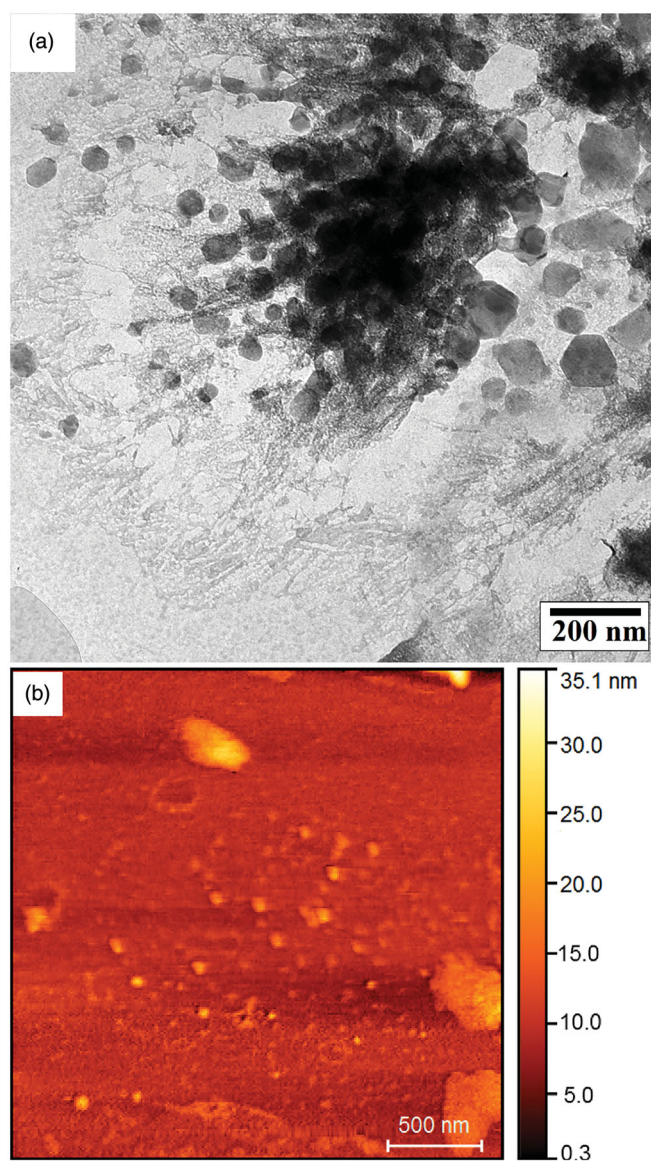


Figure 5. TEM image (a) and AFM with the 3D scale of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanostructure related to sample 1 (b).

was calculated from the translational diffusion coefficient by using the Stokes-Einstein equation (Eq. 3).

$$d(H) = kT/3\pi\eta D \quad (3)$$

where $d(H)$, D , k , T , and η denote the hydrodynamic diameter, translational diffusion coefficient, Boltzmann constant, absolute temperature, and viscosity, respectively. The diameter of the particles which can be measured with DLS is a value displays how a particle diffuses within a fluid; therefore, it is referred to the hydrodynamic diameter. The DLS plot related to Sample 1 is depicted in Figure 3(b). The average approximate size of the nanoparticles was ~ 77 – 120 nanometres. The results show that with increasing the reaction temperature, the agglomeration of the active surface of the nanoparticles took place, that can be attributed to the higher nucleation and growth processes.

SEM was used to investigate the surface properties as well as the morphological and particle size distribution of the nanostructures. The SEM images of the final samples

prepared via the hydrothermal method at 150 , 180 , and 200°C at 4 h are illustrated in Figure 4(a–c).

The as-synthesised $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ samples from 150 to 200°C showed shapes as well as morphological and size distributions. The nanostructures as-synthesized with the hydrothermal method at 150°C after 4 h had more uniform size and shape distribution. The results showed that at lower temperatures, such as 150 and 180°C , since nucleation and growth processes were under control, enough energy to create spherical and separate nanoparticles was available. Based on SEM images, upon increasing the reaction temperature to 200°C , decentralized clusters and the agglomeration zone are created, which can be due to the increased surface area-to-volume ratio. In order to examine the effect of the hydrothermal method in the synthesis of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanoparticles, a sample was tested with the co-precipitation method. The SEM image in Figure 4(d) shows a large particles size and amorphous structure synthesized by the co-precipitation method;

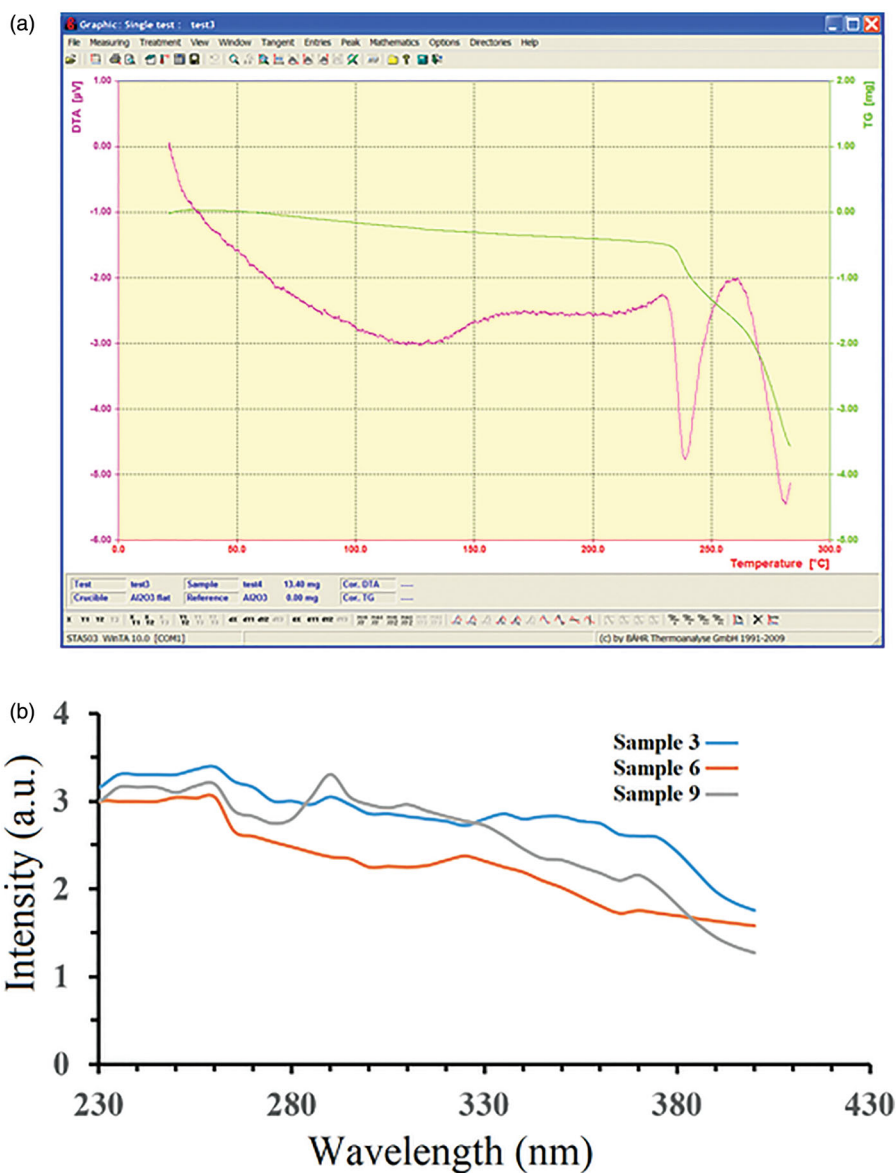


Figure 6. TGA/DTA diagrams of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanostructure (a) and the UV-vis spectra of samples 3, 6 and 9 at room temperature (b).

therefore, the method can have a significant impact on the formation of nanoparticles.

According to the SEM images and DLS analysis, the formation of nano-sized $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ structures with the least agglomeration is related to the sample at 150°C after 4 h with the hydrothermal method. To better understand the morphological and particle distribution and particle shape, Sample 1 was investigated by TEM in Figure 5(a). The particles have a spherical shape, and their distribution is uniform. TEM results are in good agreement with SEM image results and also display the formed structures with a uniform distribution. The roughness, the elastic modulus of the interface, and the surface morphology of the samples with a scale size ranging from microns to sub-nanometres were characterized by AFM at the 3 D and 2 D scales in Figure 5(b).

Based on the AFM analysis, the nanoparticles have spherical-like and homogenous structures. By comparing the surface roughness of the samples, it was found that some large particles and agglomerates existed in some places, and this can be attributed to the very active surface of the nanoparticles. To evaluate the thermal stability and understand the thermogravimetric analysis, in which the mass of the samples is measured over time as the temperature changes, the TGA diagram of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanoparticles related to Sample 1 is illustrated in Figure 6(a). The TGA/DTA analysis curve reveals the one-step degradation stages for the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ nanoparticles. The decomposition temperatures appear at $\sim 238^\circ\text{C}$. This could be due to the thermal de-polymerization of the HAp structures. Finally, the rest of the structure up to 265°C is destroyed completely. The good temperature stability of the HA nanostructures is due to the creation of a larger surface-to-volume ratio and, consequently, the presence of pores to increase the resistance of inter-molecular bonds. Also, the nanoparticles trapped in the network of BioMOFs as a substrate structure yield greater thermal stability. The optical properties of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ structures were investigated by UV-vis spectroscopy. The UV-vis spectra of Samples 3, 6, and 9 in distilled water as a solvent at room temperature are displayed in Figure 6(b). The UV-vis spectra consist of one peak at $\sim 290.5\text{ nm}$ related to Sample 9 that can be attributed to a high level of transition in HAp crystallites. The results showed that by decreasing the reaction temperature from 200 to 150°C , a blue shift is observed at the wavelength of 245 nm. This blue shift of the $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2/\text{Li-BioMOFs}$ structures related to Samples 6 and 3 can be due to the quantum size effect as well as the decreased band gap though the smaller particle size in quantum dot nanoparticles. Other samples showed no definite peak, indicating the absence of a crystalline structure.

The mechanical properties of nano-HAp structures, such as tensile strength (MPa) and Young's modulus (GPa), were improved by the addition of nano-bio Li/MOFs in the concentration range from 0 ppm (wt) up to 100 ppm (wt) (Figure 7(a)). Results indicated that the mechanical properties of nano-HAp structures in 60 ppm (wt) Li-BioMOF were increased by $\sim 132.5\text{ MPa}$ and 11.5 GPa for the flexural and Young's modulus, respectively, compared with the composite without Li-BioMOF structures. The mechanical characteristics of nano-HAp structures depend on intermolecular Li-BioMOF

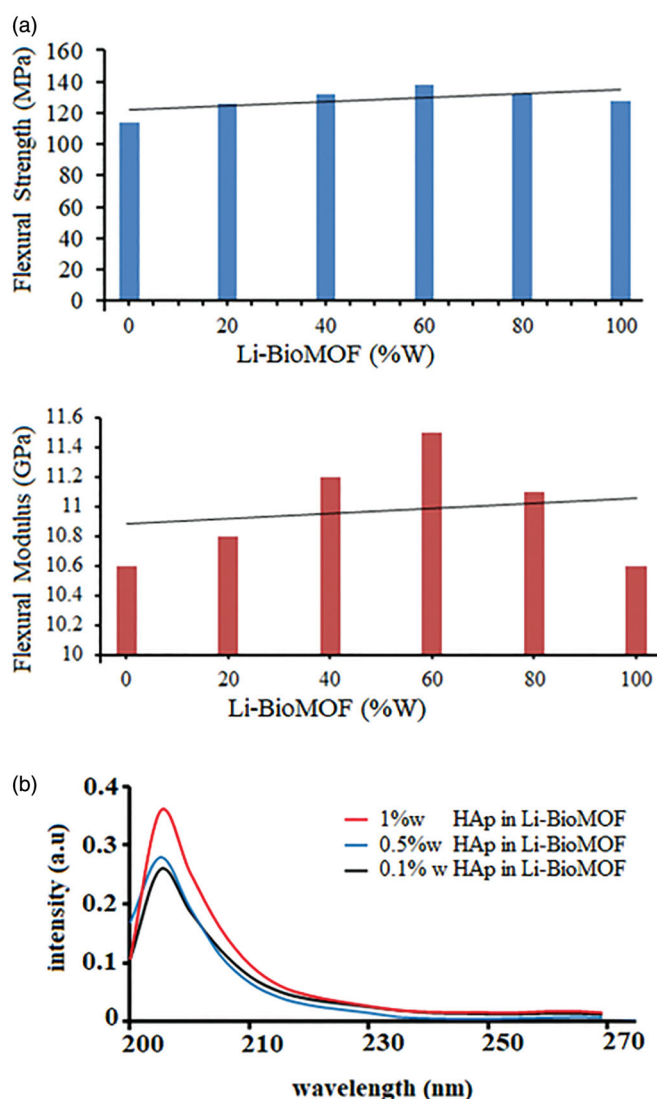


Figure 7. Mechanical properties of the HAp nanostructures with different concentration of the Li-BioMOF flexural strength and flexural modulus (a) and the UV-vis spectra of HAp nanostructures concentrations such as 1%w, 0.5%w and 0.1%w added to Li-BioMOF (b).

structures with porous and unique properties, creating a widespread network of coherence in the final products. The existence of Li-BioMOF structures $>60\text{ ppm}$ (wt) causes the loss of flexural and Young's modulus due to a collapse in the network of the metal organic framework structure. To determine the optical properties and absorption, different concentrations of HAp nanostructures such as 1, 0.5, and 0.1% w were added to Li-BioMOF structures. Based on the results, in general, adding HAp nanostructures to Li-BioMOF structures reduced network defects in the structures, and blue shift occurred. The UV-vis spectra of different concentrations of HAp nanostructures such as 1, 0.5, and 0.1% w added to Li-BioMOF structures are demonstrated in Figure 7(b).

Conclusion

In this study, for the first time, NHA structures were synthesized with *Glycyrrhiza glabra* (liquorice) root juice which acted not only as a green capping agent, but also as a reducing

agent in reaction. It was observed that the mechanical properties of HAP structures are improved with adding Li-BioMOF structures that are as a class of biocompounds consisting of metal ions or clusters coordinated to green organic ligands to form one-, two-, or three-dimensional structures. The tensile strength (MPa) and Young's modulus (GPa) of nanocrystalline HAP were significantly improved by the addition of 60 wt% of Li-BioMOF structures. The Li-BioMOFs substrates for $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ nanostructures were synthesized in the presence of lecithin as a bio-stabilizer. Results showed that Li-BioMOFs acts as a suitable substrate and improves the HA mechanical properties. The processed nanocomposites were characterized by XRD, SEM, TEM, AFM, DLS, Uv-vis, and FT-IR. Based on the findings, at lower temperatures in the hydrothermal method, such as 150 and 180 °C, the nucleation and growth processes were under control; therefore, Sample 1 was selected as the optimum sample in terms of size and uniformity distribution.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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