Okra extract-assisted green synthesis of CoFe$_2$O$_4$ nanoparticles and their optical, magnetic, and antimicrobial properties

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Abstract

Cobalt ferrite nanoparticles are synthesized using biological agents as fuel by both conventional and microwave heating methods. We focused on the green synthesis of cobalt ferrite, which is eco friendly, inexpensive, and easy to produce by large-scale synthesis. Synthesis methods were carried out under the same conditions. The role of the plant extract and advantages of microwave techniques are discussed. Plant extract-mediated nanoparticles were characterized by various techniques to analyze the size, shape, crystallinity, optical, magnetic, and antimicrobial properties. The X-ray diffraction pattern revealed single-phase crystalline structures with an average size of 45–55 nm. The functional groups present in the samples were confirmed by Fourier transform infrared spectroscopy. From SEM and DLS studies, it is confirmed that the spherical nanoparticles range in the size of 300–500 nm for CHM and 5–50 nm for MHM. Energy-dispersive X-ray spectroscopy analysis confirmed the presence of cobalt, iron, and oxygen. The energy band gap of the samples was measured by UV–Visible diffuse reflectance spectroscopy. In photoluminescence analysis, the band emission was observed in the visible region. Samples prepared by microwave heating showed better magnetic behavior than those prepared by conventional heating based on vibrating sample magnetometer analysis. The plant extract makes the synthesis of cobalt ferrite nanoparticles a potentially low-cost and ecofriendly remediation method. The synthesized nanoparticles also exhibited excellent antimicrobial activity against bacteria and fungus strains.

1. Introduction

In recent years, magnetic ceramic nanoparticles have gained considerable attention in the biomedical field because of their advantageous optical, magnetic, and antibacterial properties at the nanoscale. Ferrites, among the most important magnetic materials, can be divided into two spinel structures: normal and inverse spinels. Cobalt ferrite has an inverse spinel structure in which metal ions occupy two sub lattices, such as tetrahedral and octahedral sites. Cobalt ferrite exhibits advantages such as its low cost, good coupling efficiency, and high magnetostriction [1]. Cobalt ferrite nanoparticles can be prepared by various methods including combustion, thermal decomposition, auto combustion, sol-gel processing, co-precipitation, reverse co-precipitation, organic precursor decomposition, double sintering, citrate complex, hydrothermal synthesis, micro emulsion, mechanochemical...
synthesis, mechanical milling, and novel solvothermal approaches [2–11,65]. The particles obtained by using these methods showed the desired characteristics, but are labor-intensive to produce and may involve sintering, pH, surfactants, solvents, and organic salts, etc. They create environment pollution, are costly, require a long time for preparation, and involve labor-intensive procedures. Hence, they are not suitable for large-scale synthesis [12]. To overcome such disadvantages, we used new green methods to synthesize nanoparticles, which have received increasing attention in various research fields [13,14]. Additionally, cobalt ferrite nanoparticles synthesis strongly depends on various parameters such as crystallite size, phase purity, particle size, and optical and magnetic properties. These factors can be optimized by altering the synthesis conditions. In this study, we compared two methods: conventional (CHM) and microwave heating (MHM). Cobalt ferrite nanoparticles synthesized by conventional methods are typically agglomerated and form large nanoparticles because of the long heat treatment. Therefore, novel and green methods may reduce the particle size and heat treatment time. The microwave method was found to be suitable for achieving these goals.

Microwave irradiation gained attention for applications in various fields, such as health care, environment defense, and information [3,15]. In this method, heat is generated within the sample at the molecular level and the energy can penetrate the sample via the molecular motion. During the reaction, water can evaporate within the sample and the particles can be obtained. The oscillation of microwaves increases the rate of molecular collision, generating an enormous amount of heat. The homogeneously distributed heat is then transferred to the material interior, causing exothermic reactions followed by vigorous evolution of gases to form nanoparticles. By using microwaves, heat is produced over a short time, resulting in the early phase formation of small-sized particles [15].

Various researchers have proposed various green chemistry methods to prepare the nanoparticles. Biosynthesis using green methods with different biological systems such as plant extracts and microorganisms has been developed. Numerous reducing agents can be used in the synthesis of nanoparticles, such as sugar, amino acids, ascorbic acid, and plant extract [16,17]. Among these, plant extract is naturally available and less costly than other reducing agents. Compounds present in the plant extract may include various combinations of organic and inorganic reducing agents. Here, the reaction occurs between the aqueous plant extract and aqueous solution of metal salts at room temperature. The different reducing agents present in the plant extract may complete the reaction within few minutes. Metal nitrates are used to generate the nanoparticles, because of their high solubility and homogeneous formation, while okra (Abelmoschus esculentus) plant extract was used as the reducing agent. All solutions were prepared using deionized water.

2. Experimental

2.1. Materials

The precursors Co(NO3)2·6H2O, (Merck, Kenilworth, NJ, USA) and Fe(NO3)3·9H2O, (Merck) were used as oxidizing agents. Both chemicals were of analytical grade and used without additional refinement. Okra (A. esculentus) plant extract was used as the reducing agent. All solutions were prepared using deionized water.

2.2. Preparation of plant extract

Okra (A. esculentus) extract was prepared by using 5 g portions of crops, which were thoroughly washed without the use of toxic organic compounds. The supernatant was removed, and the inner part (gel of the plant) was finely cut and mixed with 30 mL of deionized water. This mixture was stirred for 1 h using a magnetic stirrer at 32 °C to form a homogeneous solution. The solution was filtered and used as the extract.

2.3. Synthesis of CoFe2O4 nanoparticles by conventional heating method

Cobalt nitrate (Co(NO3)2·6H2O) and ferric nitrate (Fe(NO3)3·9H2O) in a 1:2 molar ratio were dissolved in double-distilled water and then stirred to obtain a homogeneous clear solution. The extract of Okra (A. esculentus) plant was then added dropwise to the solution under vigorous stirring for several hours at room temperature until a very clear solution was obtained. The solution was placed in a hot air oven at 180 °C for 3 h for drying. The obtained powder was ground using a mortar and pestle and then sintered at 1000 °C for 3 h in a muffle furnace. The final powder was washed with ethanol and labeled as CHM.

2.4. Synthesis of CoFe2O4 nanoparticles microwave heating method

The clear solution containing the metal nitrates and plant extract after vigorous stirring were placed in a silica crucible and irradiated at a frequency of 2.54 GHz at 850 W output power for 15 min using a domestic microwave oven. First, the solution began to boil, causing dehydration, and later evolved an enormous amount of gases through decomposition. The point of spontaneous combustion, at which burning of the solution followed by vaporization resulted in the formation of a solid, confirmed the completion of the reaction. The obtained powder was ground in a mortar and pestle, washed with ethanol, and dried in a hot air oven at 100 °C for 1 h. The final powder obtained was labeled as MHM. The single-phase crystallinity was formed within 15 min after combustion under microwave irradiation only without further
calcination treatment. But it was achieved at 1000 °C for 3 h in CHM.

2.5. Characterizations

XRD was performed to detect the structural phases using a high-resolution Rigaku Ultima IV (Tokyo, Japan). Rietveld refinement was conducted using the PDXL program to calculate lattice parameters. FTIR was conducted using a Perkin Elmer infrared spectrophotometer (Waltham, MA, USA) in the range 4000–400 cm⁻¹. SEM measurements were carried out using a VEGA 3 TESCAN. EDX measurements were carried out using a vibrating sample magnetometer (PMC MicroMag3900 with 1T magnet; Lakeshore Cryotronics, Westerville, OH, USA).

2.6. Antibacterial activity tests

Antibacterial activity was analyzed by the disc-diffusion method [37]. Petri plates contained 20 mL of sterile Mueller Hinton Agar (Hi-media, Mumbai, India). The cultures were grown for 24 h and then allowed to dry for 10 min. The tests were conducted using 10 mg/mL concentrations of the given sample. For the assay 25, 50, and 100 μL of the sample was loaded onto the disc, and the disc was placed on the surface of the medium and left for 30 min at room temperature for diffusion. Streptomycin (10 μg/disc) was used as a positive control. The plates were incubated for 24 h at 37 °C. The zone of inhibition was recorded in millimeters.

2.7. Antifungal activity tests

Antifungal activity was evaluated using a standard method [38]. Petri plates contained 20 mL of sterile Sabouraud’s dextrose agar (Hi-media). The cultures were grown for 48 h and then allowed to dry for 10 min. The tests were conducted at 10 mg concentrations of the given sample. Samples of 25, 50, and 100 μL were loaded onto the disc and placed on the medium surface and left for 30 min at room temperature for diffusion. Fluconazole was used as a positive control. The plates were incubated for 24 h at 28 °C. The zone of inhibition was recorded in millimeters.

3. Results and discussion

3.1. Crystal structure

The cobalt ferrite nanoparticles prepared by CHM and MHM using non-hazardous plant extracts exhibited crystallite sizes of 47 and 55 nm, respectively, as determined by XRD analysis. The crystallographic information obtained by XRD is displayed in Fig. 1. The XRD pattern of (a) CoFe₂O₄-CHM and (b) CoFe₂O₄-MHM nanoparticles was as follows:

\[ D = \frac{k\lambda}{\beta \cos \theta} \]

where D, k, λ, β, and θ are crystallite size, Scherrer constant, wavelength of the X-ray, full width half-maximum of the (311) plane, and Bragg diffraction angle, respectively. The diffracted peak intensities increased and full width half-maximum of the peak decreased because of the calcination temperature in CHM (Fig. 1a). The reflection of all peaks sharpened and crystallinity was improved, resulting in larger crystallite sizes. The increased crystallite size with increasing calcination temperature has been reported previously [39]. For MHM (Fig. 1b), diffraction peak intensities decreased and full width half-maximum increased. Hence, based on the XRD data, we compared the patterns of CHM with that of MHM, which revealed that particle sizes generated by MHM were smaller than those generated by CHM; CHM samples showed higher crystallinity and larger particle size. This can be explained based on coalescence and Ostwald ripening [40]. As temperature increased, free atoms in the solutions were supersaturated, leading to their encapsulation on the surface of larger particles. Therefore, the smaller particles shrunk and the larger particles grew [41]. Additionally, during the calcinations process, the smaller particles present on the surface melted and fused together to form larger nanoparticles. A previous study reported that grain growth also affects particle size during calcination [42].
in CHM, structural deviation was greater and showed a higher refinement value compared to MHM. Thus, the method used to prepare nanomaterials also affects the deviation of the above results. The lattice parameters of the samples are 8.4 Å and 8.4 Å for CHM and MHM respectively. Therefore, CHM and MHM have identical lattice parameters. But, the slight decrease in the lattice parameter with increasing annealing temperature for the Ni-Zn ferrite system was reported by Naughton et al. They suggested that the -OH group present in the sample disappeared during heat treatment at approximately 900 °C and the lattice parameter of the nanoparticles may be diminished. In our study, the sample prepared by MHM showed a higher lattice parameter value without calcination because of the lower value of microstrain. However, both samples showed values lower than the reported value (8.392 Å) [45]. The slight difference in the lattice parameter is likely related to crystal defects, size effects, and surface distortion of the nanoparticles. Additionally, the distribution between the metal cations (Fe, Co) in the inverse spinel structure of CoFe2O4 nanoparticles affects the lattice parameters of the materials [46].

### 3.3. FT-IR analysis

FT-IR is used to identify the chemical bonding, impurity, defects, and elemental constitution of samples. Fig. 3a and b show the FT-IR analysis of the CHM and MHM samples. The spectrum consists of tetrahedral and octahedral position of the CoFe2O4 nanoparticles reflected in two persistent absorption peaks in a lower frequency region of approximately 599 and 425 cm⁻¹ for CHM and 597 and 434 cm⁻¹ for MHM, respectively. These two prominent peaks were assigned to the metal oxide mode of the as-prepared samples. The strong relevant peak of CoFe2O4 showed Fe-O absorbance at 599 and 597 cm⁻¹. The bands at 425 and 434 cm⁻¹ were attributed to the stretching modes of Co-O [47]. The position of the peak varied because of differences in the synthesis methods and grain sizes of the samples [48]. IR bands due to O-H group were observed at 3400 and 1600 cm⁻¹, which originated because of the stretching and bending vibration of water molecules [49].

### 3.4. EDX analysis

EDX analysis revealed the formation of pure CoFe2O4 nanoparticles; a pictorial representation of the samples is shown in Fig. 4. Element intensity increased, which agreed with the expected stoichiometry three elements (Fe, Co, O) were detected in the

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Crystallite size (nm)</th>
<th>Microstrain (%)</th>
<th>Lattice parameters (Å)</th>
<th>Rwp (%)</th>
<th>Refinements factors</th>
<th>Rp (%)</th>
<th>Re (%)</th>
<th>S</th>
<th>χ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHM</td>
<td>55</td>
<td>0.057</td>
<td>8.4</td>
<td>26.80</td>
<td>15.92</td>
<td>22.44</td>
<td>1.25</td>
<td>1.56</td>
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</tr>
<tr>
<td>MHM</td>
<td>47</td>
<td>0.031</td>
<td>8.4</td>
<td>24.71</td>
<td>15.39</td>
<td>21.73</td>
<td>1.13</td>
<td>1.29</td>
<td></td>
</tr>
</tbody>
</table>
CoFe$_2$O$_4$ nanoparticles. According to EDX analysis, the Co element intensity decreased and Fe ratio (1:2). No other elements were detected in the sample, indicating the high purity of the synthesized samples. The results of XRD and FT-IR studies agreed well with those of EDX analysis. Thus, the elements were effectively incorporated into the CoFe$_2$O$_4$ samples and contained no impurities.

3.5. SEM analysis

Fig. 5a and b show the SEM images of magnetic CoFe$_2$O$_4$ nanoparticles prepared by CHM and MHM, respectively. As shown in Fig. 5a, the CHM sample formed a crystalline phase in some nanoparticles. However, the particles were not uniformly arranged because of the high crystallinity of the sample, which was confirmed by XRD. The grain size was increased, and the particles were somewhat loosely bound because of the high calcination temperature. Because of the larger size of the nanoparticles, the surface area of the sample was decreased. Morphological analysis of MHM samples revealed particles of tiny size which were uniformly distributed and aggregated (Fig. 5b) because of the magnetic nature and smaller crystallite size of the material. Thus, the particles were smaller in size and tightly bound. There was no significant variation in nanoparticles size and nearly all particles were spherical in shape. These results demonstrate that calcination temperature affects the CoFe$_2$O$_4$ microstructure in CHM. Thus, the MHM sample showed better morphology than the CHM sample.

3.6. DLS studies

The DLS studies presented in the Fig. 6a and b showed the average size of the synthesized CoFe$_2$O$_4$ nanoparticles obtained by CHM and MHM. The result obtained by SEM and DLS studies confirmed the presence of spherical nanoparticles and the size of the nanoparticles in CHM in the range 300–500 nm while that for the MHM is 5–50 nm. The average size of the particles synthesized by CHM and MHM as 445 and 12 nm respectively. The standard deviations of the nanoparticles are 514 and 15 respectively. The average sizes of the particles obtained from SEM are different from DLS studies. This might be due to the solvation properties that have taken place in DLS studies. Here, DLS allows observing the sample only in the solvated state where there will be solvent molecule associated with the nanoparticles. But in the case of SEM analysis, the sample is observed in the dry state (most compact state).
3.7. DRS studies

The optical characteristics of both CHM and MHM nanoparticles were investigated in the range of 200–800 nm (Fig. 7a and b). The reflectance data are presented as $F(R)$ value, obtained by the application of Kubelka-Munk method,

$$F(R) = \frac{(1 - R)^2}{2R},$$

where $R$ is the measured reflectance. The band gap energy values of the samples are 2.09 eV for CHM and 1.96 eV for MHM. This information was used to characterize the semiconducting materials, which can explain the quantum size effect of the nanoparticles by absorption edge. Reflectance directly affects the perceived color of the samples in the visible range. Both nanoparticles transmitted light in the visible region. However, there was a slight difference between samples. The MHM sample exhibited lower band gap energy than the CHM sample. The higher $E_g$ in CHM was attributed to the higher temperature used during synthesis. The slight shift in transmittance between samples was due to the grain boundary and synthesis temperature [52]. The calcination temperature decreased the concentration of oxygen vacancy in CHM, and thus, the band gap energy increased [53]. However, energy band gap decreased because of the higher oxygen vacancies present in MHM. Thus, a minimum amount of energy is needed to excite the electrons in MHM, whereas in CHM, because of the higher calcination temperature, it is difficult to excite the electrons from the valence band to the conduction band. The increase in the calcination temperature has decreased the concentration of oxygen vacancy, consequently absorption band shifted towards lower wavelength region and the band gap increases for CHM. Therefore, the energy required to excite the electrons from the O-2p-3d level increases with the calcination temperature [54].

3.8. Photoluminescence spectra

The PL emission spectra of the prepared nanoparticles at an excitation wavelength of 325 nm are shown in Fig. 8. Surface states play an important role in the luminescence characteristics of the samples. Although point defects (Schottky, Frenkel) can persist in all solids, one defect can dominate the other, as their energies are unequal. During PL processes, point defects are created by Frenkel defects because the atoms are dislocated in the nanoparticles crystal structures. Vacancies containing zinc atoms and the interstitial position occupied by ferric atoms correspond to localized acceptor states, while ferric vacancy and interstitial zinc atoms lead to donor states [55]. According to the spectra, luminous intensity of the sample was observed at two different emission wavelengths. Emission at 495 nm was attributed to green emission of the prepared nanoparticles because of the electronic transition of the interstitial atoms. The emission peak at 625 nm corresponded to yellow emission. The PL spectra of MHM and CHM were similar. Moreover, sample intensity increased only in CHM; this was not observed in MHM because of its higher calcination temperature without any shift in the peak position. When the synthesis
Magnetometry hysteresis studies of CoFe$_2$O$_4$ nanoparticles prepared by two different methods were conducted at room temperature (Fig. 9). The magnetic properties of the nanosized samples mainly depend on parameters such as lattice strain, surface spin canting, magnetocrystalline anisotropy, and synthesis method. The calculated values for coercivity and saturation magnetization of the samples are summarized in Table 2. High magnetic anisotropy was observed in the samples. The saturation magnetization ($M_s$) of the CoFe$_2$O$_4$ nanoparticles for CHM and MHM were 65.77 and 65.31 emu/g, respectively. The crystallite size and particle size were small in MHM and thus decreased the saturation magnetization. However, both samples had lower $M_s$ values than the bulk values of 80.8 and 93.9 emu/g [57]. Thus, the magnetic properties of nanosized samples depend on the preparation method, synthesis temperature, nanoparticles morphology, and nanoparticles interactions. This interaction may be related to the surface atoms and dipolar and exchange coupling of the nanoparticles. The $M_r/M_s$ value decreased in MHM and increased in CHM. The decrease in saturation magnetization in MHM was attributed to surface effects and was related to the spin order of the nanoparticles. The spin order value increases on the cobalt ferrite surface because of the smaller crystallite size. Thus, the crystallite size has a large effect on the magnetic properties of the samples. Additionally, the increase in the $M_s$ value in CHM was attributed to the decrease in thermal fluctuation on the nanoparticles surface.

It is well known that the values of remanant magnetization and coercivity are inversely proportional to grain size. The $M_s$ and $M_r$ values increased in CHM because of the increased calcination temperature, and were attributed to grain growth. Increased grain size results in low spontaneous magnetization of domain walls because of the lower volume fraction of the grain boundaries [58]. Then, the inter-sublatttice energy exchange of cations between the metal oxides in the tetrahedral and octahedral location play a major role in the variation of coercivity. Magnetocrystalline anisotropy and spin orbit coupling (L-S) also enhances the variation of coercivity. The decreased particle size with increased coercivity in MHM indicated that the magnetic properties were transformed to a super paramagnetic state from a ferromagnetic state [59]. Finally, the simple microwave heating method decreases saturation magnetization and increases coercivity of the magnetic materials.

3.10. Antimicrobial studies

The sample CHM and MHM were tested for the antibacterial activity towards Gram-negative (Enterobacter aerogenes (111) and Yersinia enterocolitica (840)), Gram-positive (Staphylococcus aureus (96) and Micrococcus luteus (106)) bacteria and fungi (Aspergillus aureus (AN) and Candida krusei (CK)) strains. Using disc diffusion method, the samples were tested at 50, 75, and 100 µL/well; the results are shown in Fig. 10a and b. Estimation of the zone inhibition in mm was carried out from mean diameter around the samples. Both samples exhibited clear bacterial zones of inhibition and thus showed better performance towards the antibacterial studies; the respective values are listed in Table 3. Based on the results, MHM shows effective antibacterial activity than the CHM sample. As the concentration increased, the inhibiting zones also increased, and the sample exhibited a different range of inhibition towards different pathogens. This may be because of the different membrane structure or cell wall integrity of the bacteria. The highest inhibition zone was observed against Y. enterocolitica (840) in bacteria and C. krusei (CK) in fungi with measured values of 16 and 15 mm, respectively. The biocidal activity of the samples was confirmed by the presence of the inhibition zone, which indicates
that the bacteria had not developed resistance towards the prepared samples [60].

Nanoparticles with a large surface to volume ratio and smaller size more readily caused abrasive action on the cell wall and ultimately caused membrane damage. Thus, biocidity was increased. When the nanoparticles cover the bacteria colony, larger amounts of reactive oxygen species are generated, and the bacteria are easily killed [61]. The MHM sample, which was smaller than the CHM sample, quickly interacted with the bacteria, and the cell membrane was completely and effectively disrupted. This directly led to the leakage of minerals, proteins, and genetic materials, finally causing cell death. Previous studies showed that for smaller particle sizes, the efficacy in inhibiting the growth of bacteria was greater; as the production of reactive oxygen species was greater [62]. Zhang et al. [63] reported that antibacterial activity increases as particle size decreases. Kooti et al. [64] reported that larger nanoparticles have a limited number of active sites for oxygen absorption on the surface because of the low surface area to volume ratio, while small size nanoparticles may easily pass through the cell membranes. Generally, a high surface to volume ratio of the nanoparticles results in better penetration and fusion with the bacterial cell membranes. Therefore, the antibacterial activity of these nanoparticles may involve the production of reactive oxygen species and accumulation of nanoparticles in the cytoplasm or on the outer membranes. Thus, the MHM sample showed better activity than the CHM sample.

4. Conclusions

We developed a green method for synthesizing cobalt ferrite nanoparticles using Okra (A. esculentus) plant extract as an effective reducing agent. Conventional and microwave methods lead to the formation of single-phase cobalt ferrites. FT-IR analysis revealed the respective functional groups on the samples. The presence of active ingredients in the plant extract stabilized the metal oxide nanoparticles. EDX analysis revealed the weight % and atomic % of the elements present in the samples. The presence of spherical nanoparticles was confirmed by SEM. From DLS studies, the size of the nanoparticles in CHM is in the range of 300–500 nm and in

<table>
<thead>
<tr>
<th>Pathogens no</th>
<th>Conc(µl/well)</th>
<th>CHM</th>
<th>MHM</th>
</tr>
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<tbody>
<tr>
<td>Staphylococcus aureus (96)</td>
<td>50 75 100</td>
<td>50 75 100</td>
<td></td>
</tr>
<tr>
<td>Micrococcus luteus (106)</td>
<td>7 10 13 11 12 14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enterobacter aerogenes (111)</td>
<td>4 6 7 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yersinia enterocolitica (840)</td>
<td>6 10 14 11 14 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspergillus aureus (AN)</td>
<td>5 9 8 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Candida Krusei (CK)</td>
<td>6 8 11 9 13 15</td>
<td></td>
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</table>

Fig. 10. Antimicrobial activity of (a) CoFe₂O₄-CHM and (b) CoFe₂O₄-MHM nanoparticles.

Table 3
Antimicrobial activity of (a) CoFe₂O₄-CHM and (b) CoFe₂O₄-MHM nanoparticles on various pathogenic bacteria and fungi strains.
MHM it is 5–50 nm. The optical bandgap of the samples was calculated in the visible region, which was confirmed by UV–Visible DRS and PL analysis. The synthesized cobalt ferrite nanoparticles existed as ferromagnets. They also have potential effects against bacteria and fungi strains, which may lead to the development of new drugs to treat various infections. Finally, the results showed that the nanoparticles synthesized using two different methods had different sizes, shapes, optical and magnetic properties, and antibacterial effects. Because of the availability of okra plant extract, the method used in this synthesis can be adopted for large-scale synthesis. Finally, we concluded that MHM has shown better structural, optical, and magnetic properties and antimicrobial activities than CHM.

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