Tuning the Properties of Ba-M Hexaferrite BaFe_{11.5}Co_{0.5}O_{19}: A Road Towards Diverse Applications

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Abstract
The development of hexaferrite nanoparticles is scrutinized as potential sorbents for the removal of chromium (Cr) ions from aqueous chromium-containing solutions in a batch adsorption experiment. The transition metal Co doped BaFe_{12}O_{19} hexaferrite compounds (BHF) have been synthesized successfully via citrate auto combustion technique. The structure, surface morphology and magnetic properties of the samples were studied. X-ray diffraction pattern ratifies the existence of hexagonal phase as a main phase for the prepared samples. The average crystallite sizes are found in the range of 47–49 nm. The high-resolution transmission electron microscopy (HRTEM), as well as the Fourier, transform infrared spectrophotometry results confirm an M-type hexagonal structure existing. The $\chi$-$T$ indicates the temperature-dependent ferromagnetic behavior of BHF nanoparticles. The derivative shows a single transition temperature $T_c$ at 698 °C, and 710 °C for BHF and BCHF respectively. The prepared samples are utilized as an adsorbent for the removal of Cr (VI) from the aqueous solution. The maximum adsorption capacity ($q_m$) of Cr (VI) on the nano hexaferrite is higher than that of various other adsorbents testified in the literature. The pseudo-second-order kinetic model gives a better fit to the experimental data.

Keywords Maximum adsorption capacity · Hexaferrite · Transition metals · Waste water · Nanoparticles

1 Introduction

One of the ferromagnetic materials which have unique magnetic properties is BaFe$_{12}$O$_{19}$ belonging to M-hexaferrite. It has a crystal structure of P6$_3$/mmc space group, which consists of SRS*R* alternative layers of hexagonal (R) and spinel (S) layers. The S* and R* layers are the same as S and R but rotated at 180° along the c-axis. One unit cell of M-hexaferrite is containing 38 O$^{2-}$ ions, two Ba$^{2+}$ ions as well as 24 Fe$^{3+}$ ions as shown in Fig. 1 [1]. The large spontaneous polarization of hexaferrite is related to 5 polyhedral sites occupied by Fe$^{3+}$. Three of them are octahedral sites having spin up related to 2a, 2b, and 12 k sites. The other two sites have spin down, one of them 4f$_1$ tetrahedral and the other is 4f$_2$ trigonal bipyramidal. Cobalt doped BHF enhances its magnetic properties as well as the adsorption of heavy metals [2].

The magneto plumbite unit cell (MFe$_{12}$O$_{19}$) of the hexaferrite system contains two formula units, consisting of 10 hexagonally close-packed oxygen layers stacked along the hexagonal basal plane (c-axis). The divalent ion, M$^{2+}$, is substituted for an oxygen atom in every fifth layer.

Barium hexaferrite is one of the important classes of materials in the family of permanent magnets due to their potential applications in numerous electronic and microwave devices. It has the broadest commercial attention due to its high magneto crystalline anisotropy, high coercivity, remanent magnetization, and large spontaneous polarization [3].

Recently, numerous methods have been built up to remove heavy metals from industrial wastewater. However, most of these techniques have some demerits as high waste treatment equipment cost, large consumption of reagents, and incompetent recovery of treated metals for reprocessing [4]. In this regard, the new developments in utilizing the adsorption process with the aid of magnetic nano particles have solved some of the problems due to their multiple and unique characteristics: high surface area, magnetic response,
easy preparation, fast adsorption kinetics, low price, and high efficiency [5].

In the present research, we aimed to prepare BaFe₁₂O₁₉ (BHF), and BaFe₁₁.₅Co₀.₅O₁₉ (BCHF) nanoparticles using the citrate auto combustion technique. This method was successful to obtain single- phase ultrafine barium hexaferrite with nano size, and excellent homogeneity. On the other hand, the obtained magnetic properties, structural analyses and morphology are comparable with those previously reported.

2 Methodology

2.1 Material Used

All chemicals Ba (NO₃)₃·6H₂O (99%), Fe (NO₃)₃·6H₂O (98%), Co (NO₃) 0.6H₂O and citric acid [C₄H₈O₇], and ammonia solution (33%) were obtained from (LOBA, India).

2.2 Experimental Technique

Nanoparticles of barium and cobalt doped Barium hexaferrite were synthesized by the citrate auto-combustion method as mentioned in the previous work [6, 7]. The proper amounts of the precursors corresponded to the stoichiometric ratios from nitrates were added. These precursors were mixed with citric acid by adding dropwise of distilled water under vigorous stirring. After that, the pH value was adjusted to 7, and the temperature was raised to 200 °C until all fumes were ended as illustrated in Fig. 2.

2.3 Characterizations and Measurements

The phase formation was determined by X-ray diffraction (analytical-x’ pertpro, Cu Kα1radiation, λ = 1.5404 Å, 45 kV, 40 mA, Netherlands). Fourier transformed infrared (FT-IR) spectra were measured in the wavenumber range of 4000–400 cm⁻¹ by FT-IR spectrometer (PerkinElmer 2000). HRTEM (HRTEM, JEOL/JME 2100) (TEM, JEOL, JSM 7001F) microscope was used for morphology study. X-ray photoelectron spectroscopy (XPS) was used to examine the chemical states of numerous elements in the prepared samples via monochromatic X-ray Al K-alpha radiation. The magnetic susceptibility of the sample was determined by the Faraday technique. A very small amount of powdered sample was placed into a cylindrical glass tube at the point of a maximum gradient in different magnetic field intensities of 1340, 1660, and 1990 Oe [8].

Fig. 1 a, b Schematic hexagonal nanoparticles and crystal structure of the M-type BaFe₁₂O₁₉. The polyhedral with different color depict the different Fe³⁺ sites with their surrounding O²⁻ ions. The yellow spheres depict the Ba²⁺ ions

Fig. 2 Schematic of preparation of BHF, and BCHF nanoparticles
3 Results and Discussion

3.1 Structure Analyses

3.1.1 XRD Diffraction

XRD patterns of BHF and BCHF hexaferrite are illustrated in Fig. 3. All indexed peaks of the studied samples are similar to ICDD card number [00-043-0002] of BHF, indicating that the obtained samples are prepared successfully in a single-phase with the space group of P63/mmc. It is observed that Co^{2+} ions completely diffused into magneto plumbite structure for samples BHF.

The diffraction pattern for BCHF has eleven broad peaks at 30.4°, 32.3°, 34.2°, 37.2°, 40.4°, 42.6°, 55.2°, 56.6° and 63.2°, corresponding to (110), (107), (114), (203), (205), (206), (217), (2011) and (220) of pure BFO and BFCO phases. The crystallite sizes D for BHF and BCHF are calculated using the Scherrer equation \[ D = \frac{K \lambda}{B \cos \theta} \] and tabulated in Table 1.

The changes in the lattice parameters can be attributed to the differences in ionic radii of Co^{2+} (0.745 Å), Fe^{3+} (0.645 Å) as well as the changes of the c-axis anisotropy with respect to the c-plane [11]. In the present study, the c/a ratio equals to 3.938, and 3.937 for pure and doped samples respectively. Additionally, the formation of oxygen vacancies is expected. The charge imbalance between trivalent ions (Fe^{3+}) is being replaced by divalent ions (Co^{2+}) altering the values of the lattice parameter as well as the unit cell volume [12].

Additionally, the theoretical density \(d_x\) is determined as mentioned earlier [13, 14] and the obtained data are tabulated in Table 1. As revealed in the Table, the presence of Co^{2+} increases the \(d_x\). This increase is due to the higher molar mass of Co^{2+} (58.933 amu) compare to that of Fe (55.845 amu) [15].

The number of dislocations in a unit volume can be measured by the dislocation density \(\delta\). The samples with fewer \(\delta\) exhibit high mechanical strength. In addition, as the \(\delta\) increases, the strength of the samples decreases. The dislocation density \(\delta\) is calculated from the following relation [16] and the results are illustrated in Table 1.

\[ \delta = \frac{1}{D^2} \] (3)

The obtained low \(\delta\) values are indications of a good crystallinity in BHF and BCHF nanoparticles.

3.1.2 FT-IR Spectra

Figure 4. reveals FT-IR spectra of BHF and BCHF hexaferrite samples in wave numbers range of 400–4000 cm\(^{-1}\). Two significant absorption bands of M-type hexaferrite, \(\upsilon_1\) and \(\upsilon_2\), are detected in the spectra. The intrinsic stretching vibrations of cation at site A–O bond are detected around

![Fig. 3 XRD Diffraction pattern of BaFe_{12}O_{19} and BaCo_{0.5}Fe_{11.5}O_{19}](image)

![Fig. 4 FTIR of BaFe_{12}O_{19} and BaCo_{0.5}Fe_{11.5}O_{19} hexaferrite samples](image)

| Sample    | Theoretical values | Calculated values |
|-----------|--------------------|-------------------|
|           | a (Å)  | c (Å)  | V (Å\(^3\)) | a (Å)  | c (Å)  | D (nm) | \(\delta\) 10\(^{-4}\) (nm\(^{-1}\)) | \(d_x\) gm/cm\(^3\) |
| BHF       | 5.890  | 23.195 | 696.88     | 5.890  | 23.196 | 49.664 | 40         | 5.297          |
| BCHF      | 5.889  | 23.187 | 696.55     | 5.889  | 23.187 | 47.825 | 43         | 5.306          |

Table 1 Lattice parameters (a and c), volume, the crystallite size (D), Dislocation density (\(\delta\)), and theoretical density (\(d_x\)) for BHF and BCHF.
584 cm\(^{-1}\). While the \(\nu_2\) is observed around 432 cm\(^{-1}\), which
is corresponding to metal ions at site B–O bond [17, 18]. Because of the short bond length of the tetrahedral cluster
consequently, tetrahedral vibration is greater than octahedral vibration [19, 20]. The presence of \(\nu_1\) and \(\nu_2\) bands ratify the
successful preparation of hexaferrite [21, 22]. While weak
bands at 1434 and, 3430 cm\(^{-1}\) are due to the carboxylate
group (C–O) [23] and for stretching vibration of (O–H)
respectively [24].

The range of absorption bands obtained is in agreement
with that reported by Mahadevan et al. [19]. The values of
transmittance bands \(\nu_1\) and \(\nu_2\) shift to a lower wave number
due to numerous reasons. The first one is the average atomic
weight of Co\(^{2+}\) ions which is smaller compared to Fe\(^{3+}\) ions
[25]. Secondly, for all the samples, the transmission band
at about 1635 cm\(^{-1}\) exhibits the stretch and bending of the
surface hydroxyl group (–OH) of M-type hexaferrite [23].

3.1.3 EDAX and Mapping Analyses

EDAX analyses for BHF and BCHF are shown in Fig. 5a–b.
The typical peaks in the spectrum include Ba, Fe, Co, and O.
The atomic percentage (at%) and weight percentage (wt%)
of component elements are obtained theoretically using the
formulas BHF and BCHF. The data acquired from EDAX
elemental analysis is depicted in the figure as an inset.

The distribution of the elements is approved by EDAX
mapping images for synthesizing samples. The results indicate
that Ba, Fe, Co, and O are uniformly distributed in the
hexaferrite structure. Thus, the samples have highly homogeneous structures, as shown in Fig. 6.

3.1.4 Microstructural Features

Figure 7 shows the HRTEM of hexaferrite samples. HRTEM
images of the testified samples display hexagonal structures.

The particles of various sizes and shapes are observed.
The particles have mostly hexagonal with rectangular
shapes which are compatible with the hexaferrite structure.
The doped samples have spherical together with hexagonal
shaped particles. Similar morphology was observed for Bar-
ium hexaferrite by Jun Young et al. [26]. The doping with a
small amount of Co\(^{2+}\) has small effect on the morphology
of particle size as detected from the figure. The magnetic
nature of the cobalt causes small agglomerations of nano
particles as shown in the images. The selected area electron

![Fig. 5](image)

**Fig. 5** EDAX for a BHF and b BCHF. The inset table provides quantitative estimates of elements determined directly from the spectrum via
weight and atomic percentages

![Fig. 6](image)

**Fig. 6** EDAX elemental mapping images of a BHF, and b BCHF
diffraction (SAED) indicates the well-defined crystalline nature and single phase nano BHF and BCHF hexaferrites (Fig. 7c, g). The data are fitted to the Gaussian distribution and the average particle size of samples are in the range of 95 nm for BHF and BCHF respectively. The obtained data from HRTEM result is in agreement with XRD results.

3.1.5 Surface Topography

Figure 8a–b show the AFM height images of BHF and BCHF nanoparticles. The height of the images reveals that the physical dimensions and thickness of the nano samples can be easily obtained from the height profiles. The roughness on the surface is indicative of the high degree of crystallographic defects, which tend to possess higher free energy and a higher surface activity [27]. Figure 8 illustrates powder's grain boundaries with comparable grain sizes for BHF and BCHF. From the images, one can detect that the grain roughness for the BHF sample is smoother than the grain roughness for the BCHF sample. The maximum peaks height of the roughness is obtained as 4.64, 6.17 nm for BHF and BCHF respectively. The difference in roughness between substituted BHF and BCHF ferrites is due to the larger particle size of the former. The roughness profile section height difference (Rdc) values for BHF and BCHF are 4.38 nm and 4.92 nm, respectively. The skewness of the roughness profile (Rsk) of BHF and BCHF are −2.26 and −1.41 respectively.

Better values of magnetic properties as will be discussed later exhibit by samples with cobalt. This is related to a more regular grain shape and a narrow grain size distribution. One can observe from AFM images that BCHF shows a regular grain shape and a larger grain roughness compared with the parent sample.

3.1.6 XPS Analysis

The composition and elements state, as well as the electronic structure and states' density in the material, can all be studied using the XPS technique. In the present work, XPS is used to study the densities of states of each element in BHF. The complete range XPS survey spectrum in the range of energies 0 to 1200 eV for BCHF with Co = 0 and 0.5 is shown in Fig. 9a–b. The peaks of Fe 2p, Ba 3d, and O 1s are detected in both samples from the survey scan spectra Fig. 9a. The Co 2p peaks, on the other hand, are exclusively detected in BCHF (Fig. 9b). The contaminating carbon is responsible for the C 1s peak at 286.24 eV [28]. The binding
energy of elements demonstrates that the BCHF is single-phase with no additional impurity phases. The peak with binding energy ≅ 531.08 eV corresponds to O confirm the presence of O$^{2-}$.

### 3.2 Magnetic Susceptibility

The thermo-magnetic plots ($\chi$) of the BHF and BCHF samples at the different applied fields are shown in Fig. 10, together with their derivative with respect to temperature. It is clear that the $\chi_m$ decreases until reaching zero point ($T_c$) with increasing temperature due to thermal energy which causes disordering of the dipoles in field direction and the material begins to act as paramagnetic material. From the figure, the increase in the field intensity reduces the values of $\chi_m$. This is due to the alignment of spin magnetic moments in field direction until all of them reach saturation (the magnetization nearly become constant) resulting in the decrease of $\chi_m$. A prominent increase of nearly 2% in the Curie temperature ($T_c$) has been detected in BCHF samples. The derivative shows a single $T_c$ at 698 °C, 710 for BHF and BCHF respectively. This indicates that the studied samples consist of a single Ba M phase. Higher $T_c$ will enable this material to be used in high-temperature magnetic devices.

The obtained data obeys the well-known Curie–Weiss law. The values of the Curie constant (C), the Curie temperature ($T_c$) Curie–Weiss constant (θ), and the effective magnetic moment ($\mu_{eff}$) are calculated from the reciprocal of $\chi_m$ with temperature (not illustrated here) as previously discussed by Ateia et al. [29, 30]. The calculated data are tabulated in Table 2.
It is clear from Table 2 that the change in magnetic parameters is associated with partial substitution of Co\(^{2+}\) ions at the octahedral site of the BHF lattice. The divalent cobalt ion Co\(^{2+}\) substituted for the trivalent iron ion Fe\(^{3+}\) will change the valence state, and consequently, a reasonable valence changes from Fe\(^{3+}\) Fe\(^{2+}\) at 2a or 4f\(_2\) sites is detected. Additionally, the valence transformation will also affect the strength of double-exchange interactions between spin-up and spin-down sublattices interaction, and T\(_c\) should be changed accordingly. The positive θ values in the Table give a strong indication of ferromagnetic behavior for the studied samples.

On the other side, the effective magnetic moment μ\(_{\text{eff}}\) slightly increases with the addition of Co. This result may be due to the occupation of Co to the tetrahedral positions which reduces the negative contribution since in BHF; the tetrahedral sites oppose the spin of most of the octahedral sites resulting in producing the net moment [31].

### 3.3 Heavy Metal Removal (HMR)

#### 3.3.1 Effect of Cr\(^{6+}\) Ion Concentration

Chromium is a highly toxic element that has a harmful effect on living organisms. Additionally, to the best of my knowledge, no such study has been reported.

The BHF and BCHF nano particles are examined at numerous experimental parameters as heavy metal concentration HMC, as well as pH to determine the optimum conditions for HMR.

The adsorption of Cr\(^{6+}\) is increased on sample surfaces by increasing the HMC till it achieved the maximum adsorption of 9%, 21% for BHF and BCHF respectively as exposed in Fig. 11a–b.

There is no further increase in the adsorption of HM after the optimum concentration (40 ppm). This behavior can be clarified due to the available active sites on the sample surface which leads to adsorption of HM at a lower concentration. By increasing the HMC, these active sites are occupied by Cr\(^{6+}\) ions more and more till the optimum concentration is achieved. At this concentration, all active sites are fully occupied and consequently, increasing the HMC above its optimum value, causing no change in adsorption of Cr\(^{6+}\) ion.

#### 3.3.2 Effect of pH on Cr\(^{6+}\) Removal

The effect of the pH solution on adsorption performance is illustrated in Fig. 11b. The BHF, as well as BCHF, have the same trend in which the increase of pH is accompanied by increasing the adsorption of heavy ions. The small value of the adsorption of Cr (VI) at low pH can be attributed to a large amount of H\(^+\) which competes with Cr\(^{6+}\) on the available
active sites [32]. The increase of pH value to 7, causes a decrease in the number of H⁺. Consequently, more active sites become available for Cr (VI) adsorption [33]. However, the ability of HM ions to form precipitates has occurred at the basic medium (pH8). Therefore, the removal of Cr (VI) ions is due to precipitation as well as adsorption. Finally, it can be detected that the adsorption efficiency of BCHF is higher compared to BHF. This result attributes to the fact that smaller crystallite size, the high surface area, as well as relatively high magnetic properties are the main causes for the observed behavior. Moreover, the rough BCHF media is able to collect a high concentration of the HMC on its surface rather than the smooth BHF.

The Langmuir and Freundlich isotherms models are used to clarify the adsorption process. Langmuir and Freundlich isotherms are expressed by Eqs. (4) and (5) respectively [34].

\[
\frac{C_e}{q_e} = \frac{1}{k_d q_m} + \frac{C_e}{q_m}
\]

\[
\ln q_e = \ln k_f + \frac{1}{n} \ln C_e
\]

where \(q_e\) and \(q_m\) (mg g⁻¹) are the adsorption capacity at equilibrium and maximum adsorption respectively, and \(k_f\) (L mg⁻¹) is the affinity binding constant, while \(k_d\) and \(n\) are physical constants signifying the adsorption capacity and intensity of adsorption, respectively.

The monolayer and heterogeneous surfaces are related to the Langmuir and Freundlich isotherms respectively [35, 36]. The investigated samples are fitting well with the Langmuir neither Freundlich isotherm models. Consequently, Cr⁶⁺ adsorption on the surface of prepared samples occurs through monolayer adsorption as detected in Fig. 12a–d.

Kinetics of HM adsorption is principally studied through pseudo-first-order (P.F.O.) or pseudo-second-order (P.S.O) kinetics. P.F.O.M. kinetic explains the physisorption. Physisorption is weak and occurs using Van der Waals forces without any chemical bonding. As a result, this process is reversible. Though, P.S.O.M. kinetic is related to chemisorption adsorption which is happened by two reactions. The first reaction extends equilibrium quickly. While the second one leaks slowly and reaches equilibrium after a long time [37, 38]. In chemisorption, bond formation exists between adsorbents and adsorbates via electron sharing. Subsequently, it is tougher than physisorption. Another kinetic model is testified by Weber and Morris I.D.M. They found that the intra particle diffusion model (IDM) is the single rate—determining the stage and the removal of adsorbate is done thought-out a rapid procedure.

The three adsorption kinetics models (P.F.O, P.S.O, & I.D.) can be clarified from the following equations

\[
P.F.O.M. \quad \ln (q_e - q_t) = \ln q_e - \frac{k_1}{2.303} t
\]

\[
P.S.O.M. \quad \frac{1}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}
\]

\[
I.D.M. \quad q_t = k_3 t^{1/2} + C
\]

where \(k_1\), \(k_2\), and \(k_3\) are the P.F.O, P.S.O, and ID rate constants in (min⁻¹) and (g mg⁻¹ min⁻¹), respectively.

The kinetics of adsorption is studied for a contact time ranging 0–60 min. The experimental data is fitted to the P.F.O and P.S.O kinetic model (Fig. 13a–d). The reported \(R^2\) value indicates that the experimental results show better fit to P.S.O kinetic model. Consequently, the adsorption of Cr (VI) by using BHF and BCHF is done through Langmuir isotherm and the adsorption mechanism kinetics is P.S.O.M

The use of only 0.02% of low-cost cobalt doped barium hexaferrite has been utilized for 35% removal of heavy metal Cr (IV) from wastewater. The specific advantages of the prepared samples are ease of separation, high adsorption per unit area, low cost as well as recycling with remarkable efficiency. This is the main novelty of the present work. Table 3 compares the heavy metals ion adsorption capacity between the present sample with other adsorbents from the literature.

The Table shows that the removal efficiency of the BHCF is much higher compared to the other adsorbents, like silica grafted, ZnOFe₂O₄, [39, 40] but lower than rick husk [41]. Overall, Cr (VI) has shown lower adsorption capacities when compared to other metals as Pb II [38], and Cd II [40]
This may be due to the adsorption mechanism of Cr (VI) ions [35]. It is very essential to take into account the different experimental conditions such as initial concentration, pH, temperature and contact time to understand and compare the adsorption behavior of each metal.

4 Conclusion

The diffraction patterns showed characteristic diffraction peaks related to the M-type Ba-ferrite structure. The Co^{2+} ions completely diffused into magneto plumbite structure for samples BaFe_{12}O_{19} causes a decrease in the crystallite size of the samples.
Table 3  Comparison of maximal heavy metal ion adsorption capacity by various adsorbents

| Adsorbent                              | Adsorbate | Removal efficiency % | References |
|----------------------------------------|-----------|----------------------|------------|
| Silica grafted on GO                   | Cr(IV)    | 9%                   | [39]       |
| ZnO·Fe2O4                              | Cr(IV)    | 7%                   | [40]       |
| Pressmud and rice husk                 | Cr(IV)    | 44%                  | [41]       |
| BHF                                    | Cr(VI)    | 10%                  | The present work |
| BCHF                                   | Cr(VI)    | 35%                  | The present work |

HRTEM data reveal that the samples have mostly hexagonal and the particle sizes are in the nano range.

The particle surface roughness can affect the magnetization of ferromagnetic particles. It facilitates their magnetization and enhanced the transition temperature.

The investigated samples are fitting well with the Langmuir either Freundlich isotherm models. Additionally, the furthermost of heavy metal ions adsorption on the surface of prepared samples has well-fitting with the pseudo-second-order kinetic model.

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Availability of Data and Material Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

1. A. Baykala, İS. Ünverb, U. Topalc, H. Sözeri, Pb substituted Ba, Sr-hexaferrite nanoparticles as high quality microwave absorbers. Ceram. Int. 43, 14023–14030 (2017). https://doi.org/10.1016/j.ceramint.2017.07.134
2. R.M. Ortiz, M.M. Garcia, J.J. Cruz-Rivera, D.V. Perez, J.R. Martinez, F.P. Moreno, A.L. Guerrero, Properties and arsenic removal evaluation of polyvinyl alcohol nanofibers with embedded strontium hexaferrite nanoparticles. Mater. Chem. Phys. 234, 151–157 (2019). https://doi.org/10.1016/j.matchemphys.2019.05.043
3. H. Nikmanesh, M. Moradi, G.H. Bordbar, R. Shams Alam, Effect of multi dopant barium hexaferrite nanoparticles on the structural, magnetic, and X-Ku bands microwave absorption properties. J. Alloys Compd. 708(1), 99–107 (2017)
4. S.M. Abdelbasir, A.E. Shalan, An overview of nanomaterials for industrial wastewater treatment. Korean J. Chem. Eng. 36(8), 1209–1225 (2019)
5. H. Shen, J. Chen, H. Dai, L. Wang, M.J. Hu, New insights into the sorption and detoxification of chromium(VI) by tetraethylenepentamine functionalized nanosized magnetic polymer adsorbents: mechanism and pH effect. Ind. Eng. Chem. Res. 52, 12723 (2013)
6. E.E. Ateia, H. Ismail, H. Elshimy, M.K. Abdelmaksoud, Structural and magnetic tuning of LaFeO3 orthoferrite substituted different rare earth elements to optimize their technological applications. J. Inorg. Organomet. Polym. Mater. 31, 1713–1725 (2021)
7. E.E. Ateia, L.M. Salah, A.A.H. El-Bassuony, Investigation of cation distribution and microstructure of nano ferrites prepared by different wet methods. J. Inorg. Organomet. Polym. Mater. 25(4), 619–1010. ISSN 1574-1443 (2015)
8. E.E. Ateia, G. Abdelatif, M.A. Ahmed, M. Abd Alla, Mahmoud effect of different Gd3+ ion content on the electric and magnetic properties of lithium antimony ferrite. J. Inorg. Organomet. Polym. Mater. 25(5), 1011–1304 (2015)
9. P.D. Thang, T.A. Ho, N.T. Dang, B.W. Lee, T.L. Phan, T.V. Manh, D.H. Kim, D.S. Yang, Mn-doped (Ba, Y)Fe2O19 hexaferrites: crystal structure and oxidation states of Mn and Fe Curr. Appl. Phys. 20, 1263–1267 (2020). https://doi.org/10.1016/j.cap.2020.08.018
10. Z. Zhang, The influence of Ce-Cu doping M-type strontium hexaferrites on structure and magnetic properties. J. Supercond. Novel Magn. 33, 3607–3613 (2020)
11. P.A. Mariño, V.A. Lapshinsky, C. Pupo, J. Matilla, A. Vega, Obtaining and structural characterization of M-type hexaferrites doped with two cations in the Fe3+ sites. KnE Eng. 3, 328–335 (2018). https://doi.org/10.18502/keg.v3i6.3011
12. D. Shekhawat, P.K. Roy, Impact of yttrium on the physical, electro-magnetic and dielectric properties of auto-combustion synthesized nanocrystalline strontium hexaferrite. J. Mater. Sci.: Mater. Electron. 30, 1187–1198 (2019)
13. E.E. Ateia, M.A. Ateia, M.M. Arman, Assessing of channel structure and magnetic properties on heavy metal ions removal from water. J. Mater. Sci.: Mater. Electron. 30, 1187–1198 (2019). https://doi.org/10.1007/s10854-021-07008-9
14. E.E. Ateia, D.E. El-Nashar, R. Ramadan, M. Farag Shokry, Synthesis and characterization of EPDM/ferrite nanocomposites. J. Inorg. Organomet. Polym. Mater. 30, 1041–1048 (2020)
15. M.E. Wieser, T.B. Coplen, Pure Appl. Chem. 83(2), 359–396 (2011). https://doi.org/10.1351/PAC-REP-10-09-14
16. E.E. Ateia, K.K. Meleka, F.Z. Ghobrial, Interplay between cation distribution and magnetic properties for CoAl1-xFe2xO3, 0.05≤x≤0.7 nanoparticles. Appl. Phys. A 127, 831 (2021)
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