

RESEARCH ARTICLE

Biosynthesis of Zinc Ferrite Nanoparticles Using Polyphenol-rich extract of *Citrus aurantium* flowers

Salar Hafez Ghoran^{1,2}, Maryam Fadaei Dashti³, Aram Maroofi⁴, Mustafa Shafiee¹, Alireza Zare-Hoseinabadi¹, Farahnaz Behzad⁵, Mohsen Mehrabi⁶, Ali Jangjou^{4*}, Kazem Jamali^{7*}

¹ Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran.

² Department of Chemistry, Faculty of Basic Sciences, Golestan University, Gorgan, Iran.

³ Clinical Research Development Unit, Shahid Rajaei Hospital, Alborz University of Medical Sciences, Karaj, Iran.

⁴ Department of Emergency Medicine, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran.

⁵ Research Institute for Fundamental Sciences (RIFS), University of Tabriz, Tabriz, Iran.

⁶ Department of Medical Nanotechnology, School of Medicine, Shahrood University of Medical Sciences, Shahrood, Iran.

⁷ Trauma Research Center, Shahid Rajaei (Emtiaz) Trauma Hospital, Shiraz University of Medical Sciences, Shiraz, Iran.

ARTICLE INFO

Article History:

Received 26 November 2019

Accepted 01 February 2020

Published 15 February 2020

Keywords:

Ferrite Magnetite

Citrus aurantium

Polyphenols

ZnFe₂O₄ nanoparticles

ABSTRACT

This study was conducted to examine the synthesis of ZnFe₂O₄ nanoparticles, using the hydroethanolic extract of *Citrus aurantium* flowers, through the application of Iron chlorides, (II) and (III), and Zinc Acetate. The as-synthesized ZnFe₂O₄ nanoparticles was adequately dispersed and stabilized in an aqueous solution through biological ligands extracted from *C. aurantium* flowers, a widely distributed plant used in the folk medicine. The active groups existing in the crude extract particularly the polyphenol compounds act like reducers and stabilizers to synthesis of nanoparticles. The synthesized magnetic nanoparticles have been identified using various practical techniques, including UV-Vis spectroscopy, TEM, DLS, XRD, FT-IR, XPS analyses, etc. The EDS and FT-IR methods were capable of detecting the presence of the Zinc element inside the nanocomposite structure. However, magnetic properties of the Zn ferrite materials are reduced significantly due to the agglomeration, particularly in aqueous solution. In this research, it was attempted to synthesize polyphenol coated Zn ferrite through the green synthesis method in order to prevent agglomeration among the nanoparticles. The FT-IR and TEM techniques confirmed the presence of polyphenols on the surface of ZnFe₂O₄ ferrite. Meanwhile, the XRD and TEM results indicated that both degree of crystallinity and particle size of the materials increased with an increase in the precipitation temperature.

How to cite this article

Hafez Ghoran N, Fadaei Dashti M, Maroofi A, Shafiee M, Zare-Hoseinabadi A, Behzad F, Mehrabi M, Jangjou A, Jamali K. Biosynthesis of Zinc Ferrite Nanoparticles Using Polyphenol-rich extract of *Citrus aurantium* flowers. *Nanomed Res J*, 2020; 5(1): 20-28. DOI: 10.22034/nmrj.2020.01.003

INTRODUCTION

Nowadays, green synthesis of nanoparticles (NPs) by use of bio-reducers is economical and eco-friendly way, without needing high pressure, high temperature, and toxic regular chemicals. Synthesis of nanoparticles using biomaterials especially plant extracts is an attractive feature because of their biocompatibilities (Kouhbanani et

al., 2019c, Talaiekhosani and Amani, 2019, Iravani, 2011). Due to natural origin of nanoparticles, the considerable toxicity was not observed when they were exposed to either body or bodily fluids. Iron-oxide magnetic NPs are the most promising materials in the field of biomedicine. Low levels of toxicity, bioavailability, substantial magnetic attitudes (superparamagnetism), and versatile surface functionalization allow different

* Corresponding Author Email: Email

biomedical applications. These include diagnostic functionalities as contrast agents in magnetic resonance imaging (Shahraki et al., 2012, Bock et al., 2009), biosensors (Hasanzadeh et al., 2015), cellular labeling (Tefft et al., 2015), and therapeutic functions including magnetic hyperthermia (Laurent et al., 2011), controlled drug release (Zhang et al., 2017), tissue reproduction (Gonçalves et al., 2017), as well as gene therapy (Cheong et al., 2009). Recently, in the area of nanodrugs, a combination of diagnosis and therapeutic functions led to coming out of intelligent nanomaterials revealing a provision of synergistic effects of nanomedicines known as “theragnostics” (Mousavi et al., 2019, Hajba and Guttman, 2016).

Ferrites are important nanomagnetic materials in the chemical industry due to their unique characteristics and potential uses, including magnetic resonance imaging, treatment of cancer, and biomedical drug delivery (Beheshtkhoo et al., 2018, Kouhbanani et al., 2018, Meidanchi et al., 2015, Issa et al., 2013). Meanwhile, the relatively high magnetic properties of zinc modified ferrite (Zn ferrite) nanoparticles have intensively attracted the researchers' attention in all areas of biomedicine and bioengineering, such as contrast-enhanced magnetic resonance imaging, cell separation, hyperthermia, detoxification of biological fluids, drug delivery, and tissue regeneration (Iacovita et al., 2019, Lohrasbi et al., 2019, Sawant et al., 2016, Issa et al., 2013, Bárcena et al., 2008). These MNPs enjoy high magnetization values and sizes smaller than 100 nanometers and thus have similar chemical and physical properties. It is also necessary that the surfaces of particles have been coated with non-toxic materials and also be biocompatible (Vatta et al., 2006, Kodama, 1999). Furthermore, metallic nanoparticles made of iron, zinc, nickel or cobalt are ignored and are easily oxidized in the presence of water and oxygen mostly due to their chemical instability for biological applications (Mousavi et al., 2018a). Therefore, coating agents, such as humic acid, gold, and silica, are normally used to protect MNPs because their core-shell structure will cause sustainable metal nanoparticles (Liu et al., 2008, Yi et al., 2005, Lin et al., 2001). Different types of capping agents, such as polyphenols were assessed as anchors for easy attachment of polyphenol coatings on magnetic nanoparticles (Hou et al., 2016, Jiang et al., 2014).

Using zinc ferrite NPs in pharmaceuticals

necessitate a comprehensive study of the plausible toxicity. In the previous studies, some useful applications have been reported such as induction of chromosomal aberration in the sunflower root meristematic cells (Foca-nici et al., 2010), the production of geno- and cytotoxicity in human amnion epithelial cell lines (WISH) (Saquib et al., 2013), oxidative stress in different human cells (Alhadlaq et al., 2015), and cytotoxicity and antioxidant activity (Kanagesan et al., 2016). The experimental inconsistencies observed in methods, materials, and used cell lines, however, make it difficult to achieve acceptable conclusions. In addition, nanotoxicological assessments should be considered as a physicochemically comprehensive characterization of the materials. Hence, the need for development of standardized nanotoxicity methods in order to utilize the promising biomedical applications is underlined. These purposes are well addressed by spinel ferrites. Zinc ferrite (ZnFe_2O_4) NPs and/or zinc-doped magnetite ($\text{Zn}_x\text{Fe}_{3-x}\text{O}_4$ ($0 < x < 1$)) NPs specifically stand out toward other ferrites because of their appropriate thermal and chemical stability (Shahraki et al., 2012) along with their lower toxicity (Wan et al., 2012). Interestingly, Iron and Zinc elements are involved in a wide range of biological processes. They are expected to be safely incorporated in the easily altered pools of both elements (Thambiayya et al., 2012, Kruszewski and Iwanenko, 2003). The system has also specific magnetic properties due to the non-magnetic nature of the zinc atom, which makes them change and improve simply through adjusting the chemical position on the NPs (Gholami et al., 2019, Shahraki et al., 2012, Naseri et al., 2011). It is essential to study the toxicity possibly induced by NP-administration relations for the potential use of zinc ferrite NPs in pharmaceuticals. These biocompatible green-synthesized nanoparticles might be applied in many areas of medicine, particularly in diagnosis and treatment of cancers, drug delivery, gene delivery, and biosensors.

A simple and single-step synthesis method was used in this study to produce safe nanoparticles. The prepared NPs were then characterized using the following techniques: TEM; transmission electron microscopy, EDS; energy-dispersive X-ray spectroscopy, XRD; X-ray diffraction, VSM; vibrating-sample magnetometer (VSM), and FT-IR; Fourier transform infrared spectroscopy.

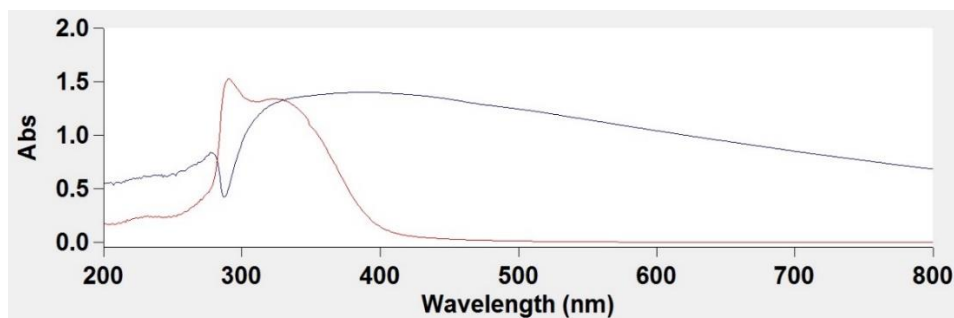


Fig. 1. The optical properties of ZnFe_2O_4 nanoparticles.

EXPERIMENTAL PROCEDURE

Materials

The analytical grade chemicals applied in this study were purchased from Merck Chemicals (Darmstadt, Hessen, Germany) and used without any further purification. These chemicals included Zinc acetate ($\text{Zn}(\text{CH}_3\text{CO}_2)_2 \cdot 2\text{H}_2\text{O}$), iron chloride (II) tetrahydrate ($\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$), iron chloride (III) hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), acetic acid (CH_3COOH), sodium hydroxide (NaOH), and ammonium hydroxide (NH_4OH , 25 wt %).

Methods

Synthesis of magnetic ZnFe_2O_4 NPs

Zinc-doped magnetite NPs, ZnFe_2O_4 , with the average diameter of 15.7 nm were prepared once a co-precipitation method using hydroethanolic extract of *C. aurantium* flowers was applied to turn the ZnFe_2O_4 nanoparticles into synthesis of sorts. To do so, 5.4 g of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ plus 1.99 g of $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and 0.8 g of $\text{Zn}(\text{CH}_3\text{CO}_2)_2 \cdot 2\text{H}_2\text{O}$ were solved in 50 ml of deionized water. This process was followed by shaking the solution strongly in order to increase the pH up to 10. Therefore, 25% of the weight of NH_4OH was also brought into the process. The ensuing reaction lasted two hours while the ambient atmosphere gas was N_2 , and the surrounding temperature was kept at 80 °C (Gholami et al., 2019). Having chilled the synthesized nanoparticles, they were then washed with deionized water until reaching to a neutral pH.

Characterization techniques

The UV-Visible absorption spectra were analyzed using a UV-visible spectrophotometer, (Varian, model; Carry 100) in the wavelength range of 200–800 nm. The visual appearance and the morphology of the ZnFe_2O_4 nanoparticles were

examined through different methods, including transmission electron microscopy (TEM), using a ZEISS 10A conventional TEM model Carl Zeiss-EM10C-100 KV (Germany). The FT-IR analyses were performed, employing a Fourier transform infrared spectrophotometer (Nicolet IS10, Thermo Scientific, USA). The wavenumbers were scanned in the range of 400–4000 cm^{-1} , using KBr pellets. A PANalytical X'Pert Pro (UK) diffractometer was used to characterize the crystalline structure characterized through Powder X-ray diffraction. A vibrating-sample (VSM, LKBFB, Meghnatis Daghigh. Kavir Co) magnetometer was used to measure magnetic properties and obtain magnetization curves.

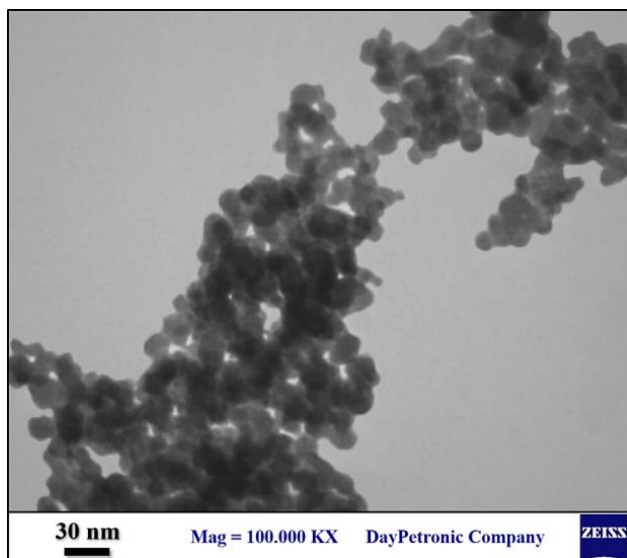
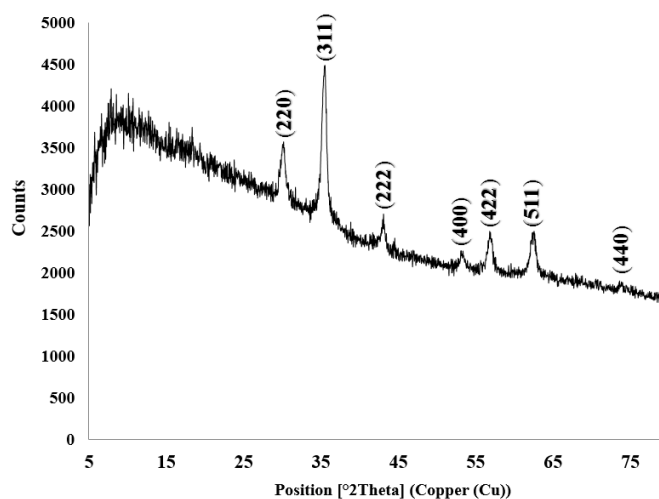
RESULTS AND DISCUSSIONS

UV-Visible spectroscopy

Fig. 1 displays the optical properties of ZnFe_2O_4 nanoparticles synthesized via ethanolic extract of *C. aurantium* flowers. According to the UV-Vis absorption spectra in the wavelength range from 200 to 800 nm, the pink spectrum is related to the polyphenols, which peaked at the ranges of 290 nm to 360 nm representing the phenolic moieties in the structures. While, the Grey graph is belonging to the synthesized Zinc ferrite NPs, the broad absorbance peak at 500 nm which could be because of electrons' excitation from O-2p to Fe-3d level in spinel type compounds (Kouhbanani et al., 2019a, Sriramulu et al., 2018, Meidanchi et al., 2015).

Transmission electron microscopy (TEM)

The TEM image of *Citrus aurantium* synthesized zinc ferrite nanoparticles makes it quite clear that the polyphenol-coated nanoparticles are very well covered. Fig. 2 illustrates the image of the synthesized ferrite magnetite nanoparticles taken by the electron microscope. Most of the

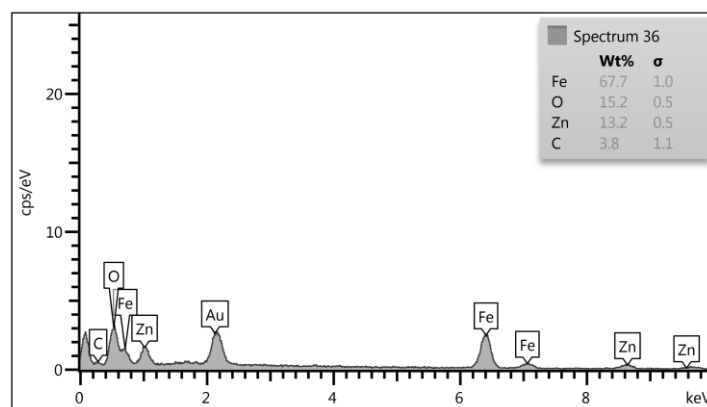
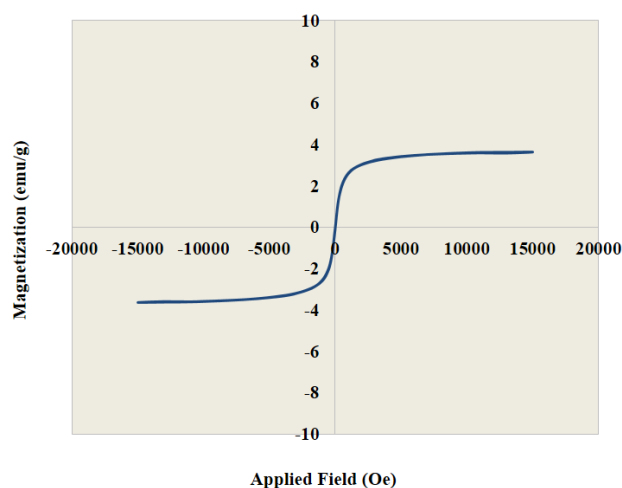
Fig. 2. TEM image of ZnFe_2O_4 nanoparticles.Fig. 3. X-ray diffraction patterns of ZnFe_2O_4 nanoparticles

synthesized nanoparticles were spherical and ranges from 9 to 20 nm in size. In terms of shape, the nanoparticles deposit significantly and show permeation interactions, which constitute one of the properties of iron nanoparticles against other metal nanoparticles and not affected by the orange extract coated on the surface of the nanoparticles. Previous studies on synthesis of Zn-doped magnetite nanoparticles have also reported similar results about shape and size (Shahraki et al., 2012, Naseri et al., 2011).

X-ray diffraction (XRD) measurements

The X-ray powder diffraction analysis was carried out to assess the crystalline phase of

the *Citrus aurantium* hydroethanolic extract-mediated ZnFe_2O_4 nanoparticles. As shown in Fig. 3, there are seven peaks 220, 311, 222, 400, 422, 511, and 440 corresponding the inverse magnetite crystal structure. The peaks are shorter than the magnetospheres reported in previous studies, implying the zinc potential to crystallize the nanoparticles in the magnet structure, based on the other studies (Tehrani et al., 2019, Kombaiah et al., 2016, Moghaddam et al., 2012). Furthermore, the absence of ZnO peak in the crystalline structure has led to the argument that all the Zn^{2+} ions involved in the reaction constitute the crystalline structure of magnetite and have no surface oxidation.

Fig. 4. EDS graph of ZnFe_2O_4 nanoparticlesFig. 5. VSM graph of the ZnFe_2O_4 nanoparticles.

Energy-dispersive X-ray spectroscopy (EDS)

Fig. 4 indicates the weight percentage of the elements making up the *Citrus aurantium* ethanolic extract-mediated ZnFe_2O_4 nanoparticles, applying EDS analysis. The obtained data revealed that zinc constituted 13.2% of the nanoparticles, which raises doubts on whether zinc is well doped in the magnet structure. This considerable amount of zinc increases the magnetic properties of magnetite nanoparticles, as in other studies where it has shown that if the magnetite structure consists of a large amount of zinc, it results in a photo and decreases the magnetic property (Kombaiah et al., 2016). The presence of carbon and oxygen elements among the elements also denotes that the polyphenol-rich extract of *C. aurantium* flowers has synthesized the nanoparticles.

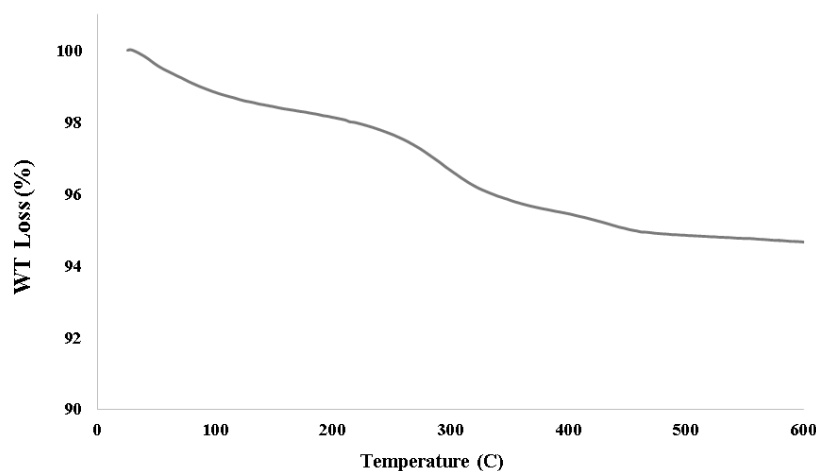
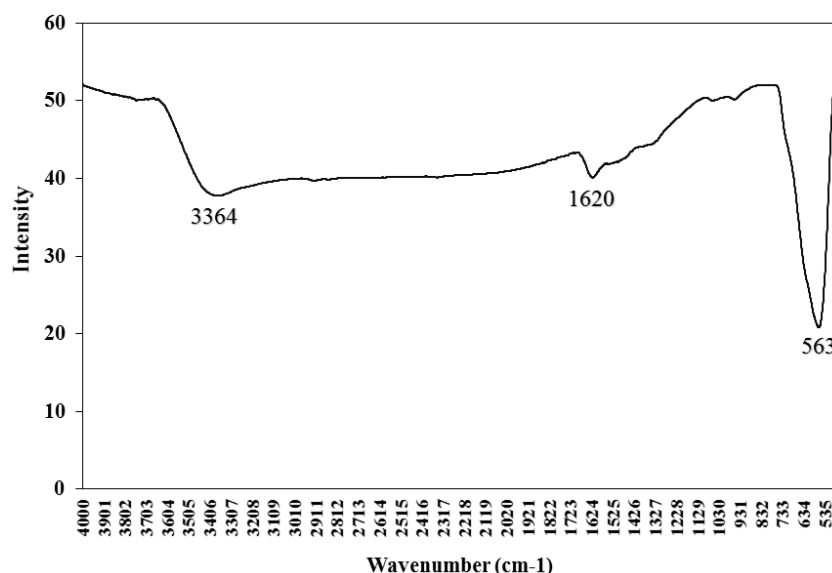
Magnetic measurements

The magnetic attitude of *Citrus aurantium*

hydroethanolic extract-mediated ZnFe_2O_4 nanoparticles was investigated using VSM technique at room temperature (Fig. 5). In terms of magnetization curve of the synthesized ZnFe_2O_4 nanoparticles, the hysteresis loop with a measurable remanence and coercivity values was observed. Likewise, the level of magnetic saturation was found to be 30 emu.g^{-1} , which is significant against the magnetic saturation (M_s) of the nanoparticles synthesized in green found in previous studies (Sriramulu et al., 2018, Yadav et al., 2017, Kombaiah et al., 2016).

Determination of thermal properties of ZnFe_2O_4 nanoparticles

The thermal stability of the green synthesized nanoparticles was evaluated through the thermal gravimetric analysis (TGA), and the nanoparticles were exposed to high temperatures of 50°C to

Fig. 6. TGA diagram of ZnFe₂O₄ nanoparticles.Fig. 7. FT-IR spectra of calcinated ZnFe₂O₄ nanoparticles.

600 °C. Since the nanoparticles were well washed with both distilled water and acetone and became maximally free from the plant extract existing on their surface, the thermal stability of the nanoparticles was increased significantly. As illustrated by Fig. 6, the weight of nanoparticles has changed up to 2% at 200 °C and 4% at 600 °C.

Fourier transform infrared (FT-IR) spectroscopy

FT-IR spectrum of synthesized zinc ferrite is shown in Fig. 7, recorded in the range of 4000-400 cm⁻¹. An general overview on the Infrared spectrum reveals certain peaks at 3364 cm⁻¹, 1620 cm⁻¹, 1430 cm⁻¹, 1053 cm⁻¹, and 563 cm⁻¹

corresponding to the various functional groups in the *C. aurantium* extract that were involved in reduction and stabilization of the nanoparticles. The peaks at 3364 cm⁻¹, 1620 cm⁻¹, and 1053 cm⁻¹ were referred as hydroxyl (-OH), aromatic (-C=C-), etheric (C-O-C) groups, respectively due to the polyphenol compounds (Kouhbanani et al., 2019b). Meanwhile, the peaks under 1000 cm⁻¹ could be related to the metal-oxygen complex, thereby the tetrahedral Zn²⁺ stretching and octahedral Fe³⁺ vibration bands of synthesized zinc ferrite nanoparticles were appeared in 400-600 cm⁻¹. Thus, a peak in the 563 cm⁻¹ represents the Fe-O group and the presence of iron oxide

nanoparticles (Lohrasbi et al., 2019, Beheshtkhoo et al., 2018, Mousavi et al., 2018b).

CONCLUSION

In the current study, a simple, cost-effective, eco-friendly method was introduced for production of zinc ferrite magnetite nanoparticles, using the hydroethanolic extract of *Citrus aurantium* flowers. The nanoparticles were produced without adding any chemicals. The biomolecules of the plant extract especially polyphenols in the process of nanoparticle production contribute to stabilization of the produced nanoparticles besides reducing the iron and zinc ions to ferrite magnetite nanoparticles. The produced nanoparticles were characterized using methods, including TEM, XRD, FT-IR, TGA, and VSM. The size distribution of the synthesized nanoparticles ranged from 9 - 20 nm, with the average size of 15.7 nm. The infrared spectroscopy studies revealed that the biomolecules containing phenol groups in the plant extract are most likely to play a key role in the production and stability of nanoparticles. The production of ferrite nanoparticles using plant extracts is very efficient and advantageous despite obvious limitations. The methods used for production of ferrite nanoparticles using plant extracts have been so far performed only *in vitro*. Extensive studies are required to optimize such methods and make them more effective in order to be able to supply the nanoparticles produced by plant extracts and the make them more competitive against those produced through common physical and chemical methods.

The main costs of producing metal nanoparticles through chemical techniques include metal precursor salts and reducing substances. However, the main costs of green synthesis of nanoparticles include only the metal precursor salt due to the possibility of using plant extracts and also food wastes as the reducing agents. Regarding the foregoing, industries, such as the food industry and the floral industry, can produce inexpensive metal nanoparticles, using plants and food wastes, besides their usual activity. Zinc ferrite nanoparticles might be used as antibacterial and also a material enhancing the antimicrobial of disinfectants and antibiotics, for treatment of cancer, hyperthermia, etc. in medicine besides the fact that the proposed synthesis of ferrite nanoparticles is easy and cost-effective, is produced out of renewable resources, and does not need complex laboratory conditions,

devices, or expensive materials. Regarding the considerable benefits and above-mentioned limitations of the proposed method, further biological studies shall be performed in order to make use of the significant characteristics of the green synthesis of zinc ferrite nanoparticles appropriately.

ACKNOWLEDGMENTS

The authors kindly thank to Shiraz University of Medical Sciences for financial support of the study [grant No. 98-01-01-20658].

CONFLICT OF INTEREST

The authors declare there is no any conflict of interest.

REFERENCES

- ALHADLAQ, H. A., AKHTAR, M. J. & AHAMED, M. 2015. Zinc ferrite nanoparticle-induced cytotoxicity and oxidative stress in different human cells. *Cell & bioscience*, 5, 55.
- BÁRCENA, C., SRA, A. K., CHAUBEY, G. S., KHEMTONG, C., LIU, J. P. & GAO, J. 2008. Zinc ferrite nanoparticles as MRI contrast agents. *Chemical Communications*, 2224-2226.
- BEHESHTKHO, N., KOUHBANANI, M. A. J., SAVARDASHTAKI, A., AMANI, A. M. & TAGHIZADEH, S. 2018. Green synthesis of iron oxide nanoparticles by aqueous leaf extract of *Daphne mezereum* as a novel dye removing material. *Applied Physics A*, 124, 363.
- BOCK, N. A., KOCHARYAN, A., LIU, J. V. & SILVA, A. C. 2009. Visualizing the entire cortical myelination pattern in marmosets with magnetic resonance imaging. *J Neurosci Methods*, 185, 15-22.
- CHEONG, S.-J., LEE, C.-M., KIM, S.-L., JEONG, H.-J., KIM, E.-M., PARK, E.-H., KIM, D. W., LIM, S. T. & SOHN, M.-H. 2009. Superparamagnetic iron oxide nanoparticles-loaded chitosan-linoleic acid nanoparticles as an effective hepatocyte-targeted gene delivery system. *International journal of pharmaceutics*, 372, 169-176.
- FOCA-NICI, E., CAPRARU, G. & CREANGA, D. Comparative cytogenetic study on the toxicity of magnetite and zinc ferrite nanoparticles in sunflower root cells. AIP Conference Proceedings, 2010. AIP, 345-350.
- GHOLAMI, M., ZARE-HOSEINABADI, A., MOHAMMADI, M., TAGHIZADEH, S., BEHBAHANI, A. B., AMANI, A. M. & SOLGHAR, R. A. 2019. Preparation of ZnXFe₃-XO₄@ chitosan Nanoparticles as an Adsorbent for Methyl Orange and Phenol. *Journal of Environmental Treatment Techniques*, 7, 245-249.
- GONÇALVES, A. I., RODRIGUES, M. T. & GOMES, M. E. 2017. Tissue-engineered magnetic cell sheet patches for advanced strategies in tendon regeneration. *Acta biomaterialia*, 63, 110-122.
- HAJBA, L. & GUTTMAN, A. 2016. The use of magnetic nanoparticles in cancer theranostics: Toward handheld diagnostic devices. *Biotechnology advances*, 34, 354-361.
- HASANZADEH, M., SHADJOU, N. & DE LA GUARDIA, M. 2015. Iron and iron-oxide magnetic nanoparticles as signal-amplification elements in electrochemical biosensing. *TrAC*

- Trends in Analytical Chemistry*, 72, 1-9.
- HOU, C., WANG, Y., ZHU, H. & WEI, H. 2016. Construction of enzyme immobilization system through metal-polyphenol assisted Fe₃O₄/chitosan hybrid microcapsules. *Chemical Engineering Journal*, 283, 397-403.
- IACOVITA, C., FLOREA, A., SCORUS, L., PALL, E., DUDRIC, R., MOLDOVAN, A. I., STIUFIUC, R., TETEAN, R. & LUCACIU, C. M. 2019. Hyperthermia, Cytotoxicity, and Cellular Uptake Properties of Manganese and Zinc Ferrite Magnetic Nanoparticles Synthesized by a Polyol-Mediated Process. *Nanomaterials*, 9, 1489.
- IRAVANI, S. 2011. Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13, 2638-2650.
- ISSA, B., OBAIDAT, I. M., ALBISS, B. A. & HAIK, Y. 2013. Magnetic nanoparticles: surface effects and properties related to biomedicine applications. *International journal of molecular sciences*, 14, 21266-21305.
- JIANG, W., LAI, K., LIU, K., XIA, R., GAO, F., WU, Y. & GU, Z. 2014. "Green" functionalization of magnetic nanoparticles via tea polyphenol for magnetic resonance/fluorescent dual-imaging. *Nanoscale*, 6, 1305-1310.
- KANAGESAN, S., HASHIM, M., AB AZIZ, S., ISMAIL, I., TAMILSELVAN, S., ALITHEEN, N., SWAMY, M. & PURNA CHANDRA RAO, B. 2016. Evaluation of antioxidant and cytotoxicity activities of copper ferrite (CuFe₂O₄) and zinc ferrite (ZnFe₂O₄) nanoparticles synthesized by sol-gel self-combustion method. *Applied Sciences*, 6, 184.
- KODAMA, R. 1999. Magnetic nanoparticles. *Journal of magnetism and magnetic materials*, 200, 359-372.
- KOMBAIAH, K., VIJAYA, J. J., KENNEDY, L. J. & BOUOUDINA, M. 2016. Studies on the microwave assisted and conventional combustion synthesis of Hibiscus rosasinensis plant extract based ZnFe₂O₄ nanoparticles and their optical and magnetic properties. *Ceramics International*, 42, 2741-2749.
- KOUBHANANI, M. A. J., BEHESHTKHO, N., AMANI, A. M., TAGHIZADEH, S., BEIGI, V., BAZMANDEH, A. Z. & KHALAF, N. 2018. Green synthesis of iron oxide nanoparticles using Artemisia vulgaris leaf extract and their application as a heterogeneous Fenton-like catalyst for the degradation of methyl orange. *Materials Research Express*, 5, 115013.
- KOUBHANANI, M. A. J., BEHESHTKHO, N., FOTOOHIARDAKANI, G., HOSSEINI-NAVE, H., TAGHIZADEH, S. & AMANI, A. M. 2019a. Green Synthesis and Characterization of Spherical Structure Silver Nanoparticles Using Wheatgrass Extract. *Journal of Environmental Treatment Techniques*, 7, 142-149.
- KOUBHANANI, M. A. J., BEHESHTKHO, N., NASIRMOGHADAS, P., YAZDANPANAH, S., ZOMORODIAN, K., TAGHIZADEH, S. & AMANI, A. M. 2019b. Green Synthesis of Spherical Silver Nanoparticles Using Ducrosia Anethifolia Aqueous Extract and Its Antibacterial Activity. *Journal of Environmental Treatment Techniques*, 7, 461-466.
- KOUBHANANI, M. A. J., BEHESHTKHO, N., TAGHIZADEH, S., AMANI, A. M. & ALIMARDANI, V. 2019c. One-step green synthesis and characterization of iron oxide nanoparticles using aqueous leaf extract of Teucrium polium and their catalytic application in dye degradation. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 10, 015007.
- KRUSZEWSKI, M. & IWANENKO, T. 2003. Labile iron pool correlates with iron content in the nucleus and the formation of oxidative DNA damage in mouse lymphoma L5178Y cell lines. *Acta Biochim Pol*, 50, 211-5.
- LAURENT, S., DUTZ, S., HÄFELI, U. O. & MAHMOUDI, M. 2011. Magnetic fluid hyperthermia: focus on superparamagnetic iron oxide nanoparticles. *Advances in colloid and interface science*, 166, 8-23.
- LIN, J., ZHOU, W., KUMBHAR, A., WIEMANN, J., FANG, J., CARPENTER, E. & O'CONNOR, C. 2001. Gold-coated iron (Fe@ Au) nanoparticles: synthesis, characterization, and magnetic field-induced self-assembly. *Journal of Solid State Chemistry*, 159, 26-31.
- LIU, J.-F., ZHAO, Z.-S. & JIANG, G.-B. 2008. Coating Fe₃O₄ magnetic nanoparticles with humic acid for high efficient removal of heavy metals in water. *Environmental science & technology*, 42, 6949-6954.
- LOHRASBI, S., KOUHBANANI, M. A. J., BEHESHTKHO, N., GHASEMI, Y., AMANI, A. M. & TAGHIZADEH, S. 2019. Green Synthesis of Iron Nanoparticles Using Plantago major Leaf Extract and Their Application as a Catalyst for the Decolorization of Azo Dye. *BioNanoScience*, 9, 317-322.
- MEIDANCHI, A., AKHAVAN, O., KHOEI, S., SHOKRI, A. A., HAJIKARIMI, Z. & KHANSARI, N. 2015. ZnFe₂O₄ nanoparticles as radiosensitizers in radiotherapy of human prostate cancer cells. *Materials Science and Engineering: C*, 46, 394-399.
- MOGHADDAM, F. M., DOULABI, M. & SAEIDIAN, H. 2012. Controlled microwave-assisted synthesis of ZnFe₂O₄ nanoparticles and their catalytic activity for O-acylation of alcohol and phenol in acetic anhydride. *Scientia Iranica*, 19, 1597-1600.
- MOUSAVI, S. M., HASHEMI, S. A., ESMAEILI, H., AMANI, A. M. & MOJOUTI, F. 2018a. Synthesis of Fe₃O₄ nanoparticles modified by oak shell for treatment of wastewater containing Ni (II). *Acta Chimica Slovenica*, 65, 750-756.
- MOUSAVI, S. M., HASHEMI, S. A., GHASEMI, Y., AMANI, A. M., BABAPOOR, A. & ARJMAND, O. 2019. Applications of graphene oxide in case of nanomedicines and nanocarriers for biomolecules: review study. *Drug metabolism reviews*, 51, 12-41.
- MOUSAVI, S. M., HASHEMI, S. A., GHASEMI, Y., ATAPOUR, A., AMANI, A. M., SAVAR DASHTAKI, A., BABAPOOR, A. & ARJMAND, O. 2018b. Green synthesis of silver nanoparticles toward bio and medical applications: review study. *Artificial cells, nanomedicine, and biotechnology*, 46, S855-S872.
- NASERI, M. G., SAION, E. B., HASHIM, M., SHAARI, A. H. & AHANGAR, H. A. 2011. Synthesis and characterization of zinc ferrite nanoparticles by a thermal treatment method. *Solid State Communications*, 151, 1031-1035.
- SAQUIB, Q., AL-KHEDHAIRY, A. A., AHMAD, J., SIDDIQUI, M. A., DWIVEDI, S., KHAN, S. T. & MUSARRAT, J. 2013. Zinc ferrite nanoparticles activate IL-1b, NFKB1, CCL21 and NOS2 signaling to induce mitochondrial dependent intrinsic apoptotic pathway in WISH cells. *Toxicology and applied pharmacology*, 273, 289-297.
- SAWANT, V., BAMANE, S., SHEJWAL, R. & PATIL, S. 2016. Comparison of drug delivery potentials of surface functionalized cobalt and zinc ferrite nanohybrids for curcumin in to MCF-7 breast cancer cells. *Journal of Magnetism and Magnetic Materials*, 417, 222-229.
- SHAHRABI, R. R., EBRAHIMI, M., EBRAHIMI, S. S. &

- MASOUDPANAH, S. 2012. Structural characterization and magnetic properties of superparamagnetic zinc ferrite nanoparticles synthesized by the coprecipitation method. *Journal of Magnetism and Magnetic Materials*, 324, 3762-3765.
- SRIRAMULU, M., SHUKLA, D. & SUMATHI, S. 2018. Aegle marmelos leaves extract mediated synthesis of zinc ferrite: Antibacterial activity and drug delivery. *Materials Research Express*, 5, 115404.
- TALAIEKHOZANI, A. & AMANI, A. M. 2019. Enhancement of cigarette filter using MgO nanoparticles to reduce carbon monoxide, total hydrocarbons, carbon dioxide and nitrogen oxides of cigarette. *Journal of Environmental Chemical Engineering*, 7, 102873.
- TEFFT, B. J., UTHAMARAJ, S., HARBURN, J. J., KLABUSAY, M., DRAGOMIR-DAESCU, D. & SANDHU, G. S. 2015. Cell labeling and targeting with superparamagnetic iron oxide nanoparticles. *JoVE (Journal of Visualized Experiments)*, e53099.
- TEHRANIAN, P., SHOKUH FAR, A. & BAKHSI, H. 2019. Tuning the Magnetic Properties of ZnFe₂O₄ Nanoparticles Through Partial Doping and Annealing. *Journal of Superconductivity and Novel Magnetism*, 32, 1013-1025.
- THAMBIAYYA, K., KAYNAR, A. M., CROIX, C. M. S. & PITT, B. R. 2012. Functional role of intracellular labile zinc in pulmonary endothelium. *Pulmonary circulation*, 2, 443-451.
- VATTA, L. L., SANDERSON, R. D. & KOCH, K. R. 2006. Magnetic nanoparticles: Properties and potential applications. *Pure and applied chemistry*, 78, 1793-1801.
- WAN, J., JIANG, X., LI, H. & CHEN, K. 2012. Facile synthesis of zinc ferrite nanoparticles as non-lanthanide T₁ MRI contrast agents. *Journal of Materials Chemistry*, 22, 13500-13505.
- YADAV, R. S., KUŘITKA, I., VILČÁKOVÁ, J., URBÁNEK, P., MACHOVSKÝ, M., MASAŘ, M. & HOLEK, M. 2017. Structural, magnetic, optical, dielectric, electrical and modulus spectroscopic characteristics of ZnFe₂O₄ spinel ferrite nanoparticles synthesized via honey-mediated sol-gel combustion method. *Journal of Physics and Chemistry of Solids*, 110, 87-99.
- YI, D. K., SELVAN, S. T., LEE, S. S., PAPAETHYMIU, G. C., KUNDALIYA, D. & YING, J. Y. 2005. Silica-coated nanocomposites of magnetic nanoparticles and quantum dots. *Journal of the American Chemical Society*, 127, 4990-4991.
- ZHANG, K.-L., ZHOU, J., ZHOU, H., WU, Y., LIU, R., WANG, L.-L., LIN, W.-W., HUANG, G. & YANG, H.-H. 2017. Bioinspired "active" stealth magneto-nanomicelles for theranostics combining efficient MRI and enhanced drug delivery. *ACS applied materials & interfaces*, 9, 30502-30509.