

# Antibacterial Activity of The Iron-Zinc Oxide Nanoparticles Synthesized Via Electric Discharge Method

**Fereshteh Shahbazi**

IKIU: Imam Khomeini International University

**Reza Ahmadi** (✉ [re.ahmadi@eng.ikiu.ac.ir](mailto:re.ahmadi@eng.ikiu.ac.ir))

IKIU: Imam Khomeini International University

**Mohammad Noghani**

IKIU: Imam Khomeini International University

**Gholamreza Karimi**

IKIU: Imam Khomeini International University

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## Research

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# Abstract

With the increase in diseases caused by bacterial and viral infections, the need for antibiotics has increased. On the other hand, by creating drug resistance to organic moieties based antibiotics, novel antibiotics have attracted the attention of researchers. Nano-scale metal oxides are increasingly being considered for medical applications, especially as antibacterial agents. In this study, iron oxide nanoparticles (IONPs) and zinc oxide nanoparticles (ZONPs) were prepared via electrical discharge method in liquid medium by changing parameters such as wire diameter and electric current intensity. Synthesized NPs were evaluated by XRD, UV-Visible, FE-SEM, EDS, HR-TEM and TEM analyzes. Also, the antibacterial properties of these nanoparticles were evaluated in different ways against gram-positive and gram-negative bacteria.

## 1. Introduction:

Antibacterial agents play an important and influential role in various industries such as medicine, textile industry, food industry and also for disinfecting water [1–3]. Recently, metal NPs have shown unique properties in different industries and medical processes. High specific surface area and the uniform distribution of NPs has provided them widely applications [4]. Antibacterial metal nanoparticles have an effect on both gram-positive and gram-negative bacteria and cause them through various proposed mechanisms such as reactive oxygen species (ROS), membrane processes and the entry of nanoparticles into the bacteria, the release of ionic metals or direct destruction of bacterial membranes [5–7]. Among the metal NPs, IONPs and ZONPs have attracted the attention of researchers due to their high antibacterial properties and cost-effectiveness [8]. There are several cost-effective methods to synthesize IONPs and ZONPs; such as sol-gel [9], micro-emulsion [10], Thermal Decomposition [11], chemical precipitation [12], electrochemical [13], electrical arc discharge [14] and electrical wire explosion [15]. The electrical discharge method is performed in liquid or gaseous medium, which has been considered by researchers because of its cost-effectiveness and eco-friendly compared to other methods [4, 16]. Metallic wire evaporates by high voltage or current intensity. The NPs are then nucleated by cooling in a liquid or gaseous medium. With this method, it is possible to produce high purity metal NPs, oxide nanoparticles as well as composite NPs [4, 14, 15]. The properties and nature of nanoparticles synthesized by electrical discharge method depend on factors such as synthesis environment, wire diameter, nature of wire metal, geometric shape of wire, parameters related to electric current and applied voltage and other things [17, 18]. Environmental parameters such as pressure, pH, surfactant addition and temperature greatly influence the properties of the synthesized NPs [19, 20].

In this study, IONPs and Fe-Zn oxide NPs were synthesized at constant pH, in different current intensities and different wire diameters, by electric discharge in liquid medium [21]. Firstly, IONPs were synthesized by changing the diameter and current intensity parameters. Next, Fe-Zn Oxide NPs were synthesized in optimized current intensity and diameter [22]. The synthesized NPs were characterized by XRD, UV-VISIBLE, FE-SEM, TEM and HRTEM techniques. The antibacterial properties of NPs against two types of gram-positive and gram-negative bacteria were investigated by wet and dry methods.

## 2. Materials And Methods:

### 2.2. Synthesis of Fe-Zn oxide NPs:

0.2 mm ST37 wires were connected to the anode and cathode electrodes in the electrical discharge system and the arc discharge was performed in a plastic container which containing distilled water with pH = 7, the applied current was 300, 400 and 500 amps. According to the obtained results and previous researches, the current intensity of 500 amps was selected as the optimal current. Then wires with 0.3, 0.4 and 0.5mm size in diameter were employed under 500 amps current intensity for nanoparticles synthesis. In the next step, the ST37 wires were dipped into molten Zn. The Zn-coated ST37 wires were placed between anode and cathode, and then were connected to 80 V DC power. With starting electrical discharge process, the atoms evaporate and then cool rapidly in a liquid medium to form oxide NPs. Figure 1. shows the schematic of electric discharge method process and Table 1 summarized codes of samples.

Table 1  
Specifications of synthesized samples prepared via electric discharge method in distilled water with pH = 7

Sample code	Current Intensity (A)	Diameter (mm)
S01	300	0.2
S02	400	0.2
S03	500	0.2
S04	500	0.3
S05	500	0.4
S06	500	0.5
S07	500	0.2

## 2.3. Characterization of Fe-Zn oxide NPs:

Synthesized samples were characterized using X-ray diffractometer (XRD, model PANalytical with Cu K<sub>α</sub> radiation of 1.54060 Å, voltage 40 kV, current intensity 40 mA and step size 0.026°, The range of 2θ was 5–80°), UV-Vis spectroscopy (using UV-1800 spectrophotometer), field emission scanning electron microscopy (FESEM, Model MIRA3 TESCAN-XMU) equipped with energy dispersive spectroscope (EDS), transmission electron microscopy (TEM model Leo 912 AB) and High-resolution transmission electron microscopy (HR-TEM FEI TECNAI F20) For structural and morphological analysis.

## 2.4. Antibacterial assay:

To determine the effectiveness of a nanoparticle as an antibacterial agent, experimental techniques are used that measure bacterial survival after exposure to nanoparticles. In 2006, the Institute for Clinical and Laboratory Standards (CLSI) published a document entitled "Analysis and Presentation of Antimicrobial Sensitivity Test Data" which sets out the standards required for antibacterial testing. Gram-positive and gram-negative bacteria may react differently to antibacterial nanoparticles. Therefore, studies often include at least one gram-positive species and one gram-negative species to determine antibiotic efficacy [23, 24].

### 2.4.1. Specifications of culture medium and bacteria:

LB broth and agar powders (QUELAB Germany) were used to prepare liquid and solid culture media for bacteria, respectively. Müller-Hinton Broth (MHB) culture medium (QUELAB Germany) was also used to evaluate the minimum inhibitory concentration (MIC). The studied bacteria were gram-negative *Escherichia coli* MHD5 and gram-positive *Bacillus subtilis*.

## **2.4.2. Growth curve analysis:**

The antibacterial evaluation of the prepared nanoparticles was first performed by determining the optical density (OD). To prepare the liquid culture medium, 1.75 g of LB powder was poured into 50 ml of distilled water in an Erlenmeyer flask and placed in an autoclave at 121.5 ° C and 1.5 atmospheres for 20 minutes. Both bacteria were then inoculated separately into culture medium and placed in an incubator shaker at 37 ° C to suspend the bacterium equivalent to the 0.5 McFarland standard be prepared from any of the bacteria. Then, by adding equal amounts of bacterial suspension and adding different amounts of nanoparticles to the liquid culture medium, 4 samples with various nanoparticle concentrations of 156, 312, 625 and 1250 ppm were prepared. The samples were then placed in an incubator-shaker at 37 ° C and after each 2-hour period, the optical density at 600 nm was measured by the Spectro UV-VIS UVD-3200. The control samples used were not exposed to nanoparticles.

## **2.4.3. Minimum Inhibitory Concentration (MIC):**

To ensure the obtained antibacterial results, the antibacterial effects of the Iron Oxide and Fe-Zn Oxide nanoparticles were evaluated using standard dilution method (CLSI M07-A8).

To prepare the liquid culture medium, 1.05 g of MHB powder per 50 ml was poured into distilled water in an Erlenmeyer flask and placed in an autoclave at 121.5 ° C and 1.5 atmospheres for 20 minutes. Each bacterium was then inoculated into the culture medium separately to obtain a bacterial suspension equivalent to the half McFarland standard. 100 microliters of freshly prepared culture medium was poured into each 96-well plate well. Then 100 microliters of nanoparticle suspension was poured into the first row wells and dilution was performed from top to bottom in all wells. Then 100 microliters of the bacterial suspension was added to each cell. Two replicates were placed for each sample. One column was placed for positive control and one column for negative control. Also, one column for each sample was placed as a control sample that contained only culture medium and nanoparticles. The plates were covered with parafilm and left for 24 hours in the incubator-shaker at 37 ° C. After incubation, 40 µl of tetrazolium salt (MTT) with a concentration of 0.2 mg/ml was added to each well and placed at room temperature for 15 minutes. Growth of bacteria in wells with purple or pink appearance is determined. If the growth of bacteria is stopped, the corresponding well will appear colorless. which The concentration of that well is considered as the amount of MIC. Finally, the plate was examined with an ELISA reader with a wavelength of 600 nm. All steps related to this test were performed under a microbial hood.

## **3. Results And Discussion:**

### **3.2. NPs characterizations:**

#### **3.2.1. X-ray diffraction:**

XRD patterns of IONPs shown in Fig. 1. As can be seen, the XRD patterns reveal the characteristic diffraction peaks of cubic  $\text{Fe}_3\text{O}_4$  (ICDD no. 01-088-0315) and cubic  $\text{Fe}$  (ICDD no. 01-087-0722), respectively [8, 25]. The XRD pattern related to the S07 sample (Table 1) is presented in Fig. 2 which exhibit diffraction peaks of hexagonal  $\text{ZnO}$  (ICDD no. 01-079-0205) and cubic  $\text{ZnFe}_2\text{O}_4$  (ICDD no. 01-089-1010), respectively [1, 26, 27]. The average crystallite size of the all samples which was calculated using Scherrer's formula are presented in Table 2.

Increasing the electric current intensity increases the driving force needed to create finer nuclei of nanoparticles, the result is nanoparticles with smaller grain sizes. On the other hand, nanoparticles can form and grow both directly from plasma and from existing solid nuclei. High current intensity and high cooling rate probably lead to the formation of nanoparticles with smaller granulation [22, 28, 29].

As the wire diameter decreases and the resulting particle size decreases, the percentage of oxide phase increases. Oxidation of metal nanoparticles depends on the particle size. Oxidation is a chemical reaction and chemical reactions take place on the surface; So in order to continue the reaction, more levels must be provided for the reaction. The smaller the particle size, the greater the amount of surface atoms; Therefore, as the diameter decreases, the percentage of surface atoms that have access to oxygen due to water evaporation increases, so as the wire diameter decreases and the particle size decreases, the percentage of oxide phase increases [30, 31]. As the oxide phase increases, the antibacterial property intensifies.

The weight percentage of each phase was calculated using Rietveld method. The results are shown in Table 2. It is clear that increasing the electric current and decreasing the diameter has increased the oxide phase. Also, the percentage of metal phase in the sample with a larger diameter is higher than other samples. In other words, as the particle size increases, the metal phase increases [32].

Table 2  
Oxide and metal phase of nanoparticles.

Sample	Oxide phase (%) $\text{Fe}_3\text{O}_4$	Metal phase (%) $\text{Fe}$	Oxide phase (%) $\text{ZnO}$	Oxide phase (%) $\text{ZnFe}_2\text{O}_4$
S01	89	11	-	-
S02	90	10	-	-
S03	93	7	-	-
S04	91	9	-	-
S05	88	12	-	-
S06	85	15	-	-
S07	-	-	65	35

### 3.2.2. UV-Visible:

the UV-Visible spectra of IONPs and ZONPs are shown in Fig. 3. As can be seen, IONPs had an absorption peak in the range of 200 nm. The particle size and surface area of nanoparticles affect the absorption peak intensity. ZONPs had two absorption peaks in the range of 300 and 350 nm which are related to ZnO and ZnFe<sub>2</sub>O<sub>4</sub>, respectively [33, 34].

### 3.2.3. Field emission scanning electron microscopy:

Scanning electron microscopy images are shown in Fig. 4. It can be clearly seen that the iron oxide nanoparticles are completely uniform and spherical in shape. However, in the image related to the Fe-Zn sample particles in rod shaped and needle-shaped are seen, which is due to the presence of zinc oxide nanoparticles. FESEM images are taken from a powder sample, and also because of the magnetic nature of iron oxide nanoparticles, the aggregation of nanoparticles and the formation of clusters has been done to a large extent [16, 21, 35]. The average particle size of the samples are given in Table 3.

In the liquid media, in contrast to gaseous media, the size of nanoparticles decreases with increasing the current intensity. As the current intensity increases, the energy input to the wires increases, and fine-grained melt buds are formed during electrical discharge, and due to the high cooling rate of these fine particles, nanoparticles with smaller size are produced [21, 30, 36].

Table 3  
The average crystallite size and the average particle size of the samples according to the XRD and SEM data.

Sample	The average crystallite size (nm) (XRD)	The average particle size (nm) (SEM)
S01	17	35.85
S02	10.45	20.25
S03	8	10.3
S04	27.24	17.7
S05	29.32	26.25
S06	30.45	35.5
S07	18.46	30.9

### 3.2.4. TEM and HR-TEM:

Figure 5 shows the transmission electron microscope images of the synthesized samples. As can be seen, the synthesized iron oxide nanoparticles have a spherical and uniform morphology. With increasing current intensity from 300 amps to 500 amps, the average particle size has decreased from 26.50 nm to 11.25 nm. Also, by reducing the wire diameter from 0.5 mm to 0.2 mm, the average particle size has decreased from 33.50 nm to 11.25 nm. In addition, the images show the core-shell structure. The core contains pure iron and the shell contains iron oxide [27, 37, 38].

Figure 6. a and b show the TEM images of Fe-Zn nanoparticles. As can be seen, zinc oxide nanoparticles with a rod structure are seen. The average particle size is in the range of 20 nanometers. The core-shell structure is also clearly seen in the images. Also Fig. 6. c and d present the SAED pattern and HR-TEM images Respectively[39].

### **3.3. NPs antibacterial activity:**

#### **3.3.1. Growth curve analysis:**

Figure 7 and 8 reveal the antibacterial activity of iron nanoparticles against both bacteria. The best result is obtained in the S03 and S07 samples, which have the lower average particle size (according to SEM and XRD images) due to the higher current intensity.

in each chart, bacterial growth is reduced or completely inhibited by increasing the concentration. This phenomenon can be exacerbated by the interaction between bacteria and nanoparticles and thus the activation of antibacterial mechanisms. The effective mechanism for antibacterial effect of the iron oxide nanoparticles is the ROS production process as well as the reaction of  $Fe^{2+}$  with oxygen to produce hydrogen peroxide. Eventually,  $H_2O_2$  reacts with iron through the Fenton process to produce hydroxyl radicals that damage biological molecules[1, 26, 40].

In the case of sample S06, it is clear that it has little effect on inhibiting bacterial growth due to the presence of large nanoparticles (according to the SEM and XRD results) as well as the low percentage of  $Fe_3O_4$  in this sample. Researches has shown that the antibacterial effect of  $Fe_3O_4$  is greater than other iron compounds due to its greater oxygen supply as a good source for oxidative stress reactions.

The S07 sample showed high antibacterial properties compared to both bacteria. These results are due to the synergistic effect of the presence of iron oxide and zinc oxide simultaneously and thus activating more antibacterial mechanisms. The mechanism of action of iron oxide nanoparticles is the electrostatic interaction between nanoparticles and bacteria as well as the production of reactive oxygen species. The effective mechanisms for zinc oxide can be expressed as electrostatic interaction between nanoparticles and bacteria, production of reactive oxygen species and ion release[4, 40, 41].

#### **3.3.2. Minimum Inhibitory Concentration (MIC):**

The results of this study are collected in Tables 4 and 5. As can be seen, the iron-zinc oxide sample showed the best performance and at concentrations higher than  $312.5 \mu g / ml$  and the bacterial growth was completely stopped.

Simultaneous activation of antibacterial mechanisms of iron oxide and zinc oxide nanoparticles has created a synergistic effect in stopping the growth of bacteria. In the case of sample S06, even at the highest concentration, despite the positive effect, but complete cessation of growth is not seen. The large size of the nanoparticles has reduced the possibility of penetration into the bacterial cell and as a result is less effective[5, 40, 42].

Table 4  
the result of MIC method for E.Coli.

Concentration( $\mu\text{g/ml}$ )	S01	S02	S03	S04	S05	S06	S07	E.Coli
10000	-	-	-	-	-	0.0125	-	1.42
5000	-	-	-	-	-	0.03	-	1.491
2500	-	-	-	-	0.064	0.132	-	1.524
1250	-	-	-	-	0.1335	0.223	-	1.463
625	0.119	0.1425	0.05	0.1895	0.2625	0.406	-	1.403
312.5	0.1835	0.26	0.1245	0.2425	0.3455	0.601	0.0015	1.515
156.25	0.2245	0.3975	0.1685	0.357	0.4265	0.8875	0.102	1.468
78.125	0.3335	0.434	0.223	0.432	0.725	1.13	0.175	1.526

Table 5  
the result of MIC method for B.Subtilis.

Concentration( $\mu\text{g/ml}$ )	S01	S02	S03	S04	S05	S06	S07	B.Subtilis
10000	-	-	-	-	-	0.0125	-	0.91
5000	-	-	-	-	-	0.1065	-	0.9
2500	-	-	-	-	0.1015	0.1745	-	0.94
1250	0.099	0.072	0.006	0.0765	0.164	0.228	-	0.87
625	0.131	0.1255	0.1185	0.1455	0.269	0.421	-	0.96
312.5	0.157	0.24	0.1625	0.208	0.306	0.606	-	0.88
156.25	0.2435	0.3765	0.1825	0.348	0.4575	0.825	0.1205	1.1
78.125	0.309	0.354	0.2125	0.381	0.6125	1.029	0.1645	1.15

Figure 9. show the antibacterial effect of nanoparticles against E.Coli and B.Subtilis bacteria by MIC method, respectively. According to these diagrams, with increasing current intensity at constant diameter, the antibacterial effect is improved and also by decreasing the wire diameter at constant current, the antibacterial activity of the samples is increased. Finally, based on the results obtained in the MIC method the bacterial strain of E.Coli is more sensitive than B.Subtilis[1, 43, 44].

## 4. Conclusions

In this study, iron oxide and iron-zinc oxide nanoparticles were synthesized by electric discharge method by controlling the parameters of electric current and wire diameter. The prepared samples were microstructurally

analyzed by XRD, FESEM, UV-VISIBLE, TEM and HRTEM; The results showed that reducing the wire diameter and increasing the current have a positive effect on reducing the size of nanoparticles. Growth curve and minimum inhibitory concentration methods were used to evaluate the antibacterial properties of nanoparticles against gram-positive and gram-negative bacteria. Both bacteria showed sensitivity to nanoparticles, Fe-Zn nanoparticles showed the highest antibacterial activity.

## **Declarations**

### **Acknowledgments**

Not applicable

### **Authors' contributions**

FS: Nanoparticles Synthesis, Antibacterial tests, Writing the manuscript. RA: Supervision, Project design. MN: Writing the manuscript, preparing the synthesis system. GK: Materials characterization. All authors read and approved the final version of the manuscript.

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### **Availability of data and materials**

The datasets used and characterizations performed during this study are available from the corresponding author on reasonable request.

### **Ethics approval and consent to participate**

Not applicable

### **Competing interests**

The authors declare no competing interests.

### **Consent for publication**

Not applicable

### **Author details**

<sup>1, 2 & 3</sup> Department of Materials Science and Metallurgy, Imam Khomeini International university, Qazvin, Iran.

<sup>4</sup> Department of Mining Engineering, Imam Khomeini International university, Qazvin, Iran.

## **References**

1. Bhushan M, et al. Facile synthesis of Fe/Zn oxide nanocomposites and study of their structural, magnetic, thermal, antibacterial and cytotoxic properties. *Mater Chem Phys*. 2018;209:233–48.
2. Lewis K. Platforms for antibiotic discovery. *Nat Rev Drug Discovery*. 2013;12(5):371–87.
3. Aminov RI. The role of antibiotics and antibiotic resistance in nature. *Environ Microbiol*. 2009;11(12):2970–88.
4. Shahriyari F, et al. Synthesis and characterization of Cu-Sn oxides nanoparticles via wire explosion method with surfactants, evaluation of in-vitro cytotoxic and antibacterial properties. *Adv Powder Technol*. 2020;31(6):2337–47.
5. Hajipour MJ, et al. Antibacterial properties of nanoparticles. *Trends Biotechnol*. 2012;30(10):499–511.
6. Vidic J, et al., *Pure and multi metal oxide nanoparticles: Synthesis, antibacterial and cytotoxic properties*. *Journal of Nanobiotechnology*, 2016. 14.
7. Lemire J, Harrison J, Turner R. *Antimicrobial activity of metals: Mechanisms, molecular targets and applications*. *Nature reviews. Microbiology*, 2013. 11.
8. Zhang W, et al. Bacitracin-Conjugated Superparamagnetic Iron Oxide Nanoparticles: Synthesis, Characterization and Antibacterial Activity. *Chemphyschem: a European journal of chemical physics physical chemistry*. 2012;13:3388–96.
9. Gupta AK, Gupta M. Synthesis and surface engineering of iron oxide nanoparticles for biomedical applications. *Biomaterials*. 2005;26(18):3995–4021.
10. Malik M, Wani M, Hashim M. *Microemulsion method: A novel route to synthesize organic and inorganic nanomaterials. 1st Nano Update*. *Arabian journal of chemistry*, 2011. 5.
11. Lu A-H, Salabas EL, Schüth F. Magnetic Nanoparticles: Synthesis, Protection, Functionalization, and Application. *Angew Chem Int Ed*. 2007;46:1222.
12. Nazari M, et al. Synthesis and characterization of maghemite nanopowders by chemical precipitation method. *Journal of Nanostructure in Chemistry*. 2014;4(2):99.
13. Elrouby M, Abdel-Mawgoud AM, El-Rahman RA. Synthesis of iron oxides nanoparticles with very high saturation magnetization from TEA-Fe(III) complex via electrochemical deposition for supercapacitor applications. *J Mol Struct*. 2017;1147:84–95.
14. Kheradmand E, Delavari H, Poursalehi R. The Effect of Dissolved Oxygen in Arc Medium on Crystal Structure and Optical Properties of Iron Based Nanoparticles Prepared via Dc Arc Discharge in Water. *Procedia Materials Science*. 2015;11:695–9.
15. Song K, et al. Magnetic iron oxide nanoparticles prepared by electrical wire explosion for arsenic removal. *Powder Technol*. 2013;246:572–4.
16. Lerner MI, et al. Synthesis of Al nanoparticles and Al/AlN composite nanoparticles by electrical explosion of aluminum wires in argon and nitrogen. *Powder Technol*. 2016;295:307–14.
17. Raffi M, et al. Investigations into the antibacterial behavior of copper nanoparticles against *Escherichia coli*. *Ann Microbiol*. 2010;60(1):75–80.
18. Sundaram R, et al., *Electrical performance of lightweight CNT-Cu composite wires impacted by surface and internal Cu spatial distribution*. *Scientific Reports*, 2017. 7.

19. Lee YS, et al. Effect of ambient air pressure on synthesis of copper and copper oxide nanoparticles by wire explosion process. *Curr Appl Phys.* 2012;12(1):199–203.
20. Park E, Park HW, Lee J. Synthesis of hierarchical copper oxide composites prepared via electrical explosion of the wire in liquids method. *Colloids Surf A.* 2015;482:710–7.
21. Buazar F, Cheshmehkani A, Kassae MZ. Nanosteel synthesis via arc discharge: media and current effects. *J Iran Chem Soc.* 2012;9(2):151–6.
22. Kassae M, Buazar F, Motamedi E, *Effects of Current on Arc Fabrication of Cu Nanoparticles.* *Journal of Nanomaterials*, 2010. **2010**.
23. Horvat R. Review of Antibiogram Preparation and Susceptibility Testing Systems. *Hospital Pharmacy.* 2010;45:S6–9.
24. Seil JT, Webster TJ. Antimicrobial applications of nanotechnology: methods and literature. *Int J Nanomedicine.* 2012;7:2767–81.
25. Wasfi AS, Humud HR, Fadhil NK. Synthesis of core-shell Fe<sub>3</sub>O<sub>4</sub>-Au nanoparticles by electrical exploding wire technique combined with laser pulse shooting. *Opt Laser Technol.* 2019;111:720–6.
26. Farbod M, Movahed A, Kazeminezhad I. An investigation of structural phase transformation of monosize  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles fabricated by arc discharge method. *Mater Lett.* 2012;89:140–2.
27. Salamat S, Younesi H, Bahramifar N. Synthesis of magnetic core-shell Fe<sub>3</sub>O<sub>4</sub>@TiO<sub>2</sub> nanoparticles from electric arc furnace dust for photocatalytic degradation of steel mill wastewater. *RSC Advances.* 2017;7(31):19391–405.
28. Taccogna F. *Nucleation and growth of nanoparticles in a plasma by laser ablation in liquid.* *Journal of Plasma Physics*, 2015. 81.
29. Faraji M, Poursalehi R, Aliofkhaezrai M. The Effect of Surfactant on Colloidal Stability, Oxidation and Optical Properties of Aluminum Nanoparticles Prepared via Dc Arc Discharge in Water. *Procedia Materials Science.* 2015;11:684–8.
30. Chernavskii PA, et al. Oxidation of metal nanoparticles: Experiment and model. *Russian Journal of Physical Chemistry B.* 2007;1(4):394–411.
31. Hedberg YS, et al. Electrochemical surface oxide characteristics of metal nanoparticles (Mn, Cu and Al) and the relation to toxicity. *Electrochim Acta.* 2016;212:360–71.
32. Ahmadi S, et al. Green Synthesis of Magnetic Nanoparticles Using *Satureja hortensis* Essential Oil toward Superior Antibacterial/Fungal and Anticancer Performance. *Biomed Res Int.* 2021;2021:8822645.
33. Xu Q, et al. Hollow ZnFe<sub>2</sub>O<sub>4</sub>/TiO<sub>2</sub> composites: High-performance and recyclable visible-light photocatalyst. *J Alloy Compd.* 2015;641:110–8.
34. Vidhya K, et al. Structural and optical characterization of pure and starch-capped ZnO quantum dots and their photocatalytic activity. *Applied Nanoscience.* 2014;5:235–43.
35. Shabgard MR, Najafabadi AF. The influence of dielectric media on nano-structured tungsten carbide (WC) powder synthesized by electro-discharge process. *Adv Powder Technol.* 2014;25(3):937–45.
36. Karakoti AS, et al. Preparation and Characterization Challenges to Understanding Environmental and Biological Impacts of Nanoparticles. *Surf Interface Anal.* 2012;44(5):882–9.

37. Predescu A, et al. Synthesis and characterization of dextran-coated iron oxide nanoparticles. Royal Society Open Science. 2018;5:171525.
38. Lari L, Steinhauer S, Lazarov VK. *In situ* TEM oxidation study of Fe thin-film transformation to single-crystal magnetite nanoparticles. Journal of Materials Science. 2020;55(27):12897–905.
39. Das S, et al. Synthesis, morphological analysis, antibacterial activity of iron oxide nanoparticles and the cytotoxic effect on lung cancer cell line. Heliyon. 2020;6(9):e04953.
40. Arakha M, et al. Antimicrobial activity of iron oxide nanoparticle upon modulation of nanoparticle-bacteria interface. Sci Rep. 2015;5(1):14813.
41. Yusof NAA, Zain NM, Pauzi N. Synthesis of ZnO nanoparticles with chitosan as stabilizing agent and their antibacterial properties against Gram-positive and Gram-negative bacteria. Int J Biol Macromol. 2019;124:1132–6.
42. Rajabi SK, Sohrabnezhad S. Fabrication and characteristic of Fe<sub>3</sub>O<sub>4</sub>@MOR@CuO core-shell for investigation antibacterial properties. J Fluor Chem. 2018;206:36–42.
43. Riaz M, et al. In Vitro antibacterial activity of Ta<sub>2</sub>O<sub>5</sub> doped glass-ceramics against pathogenic bacteria. J Alloy Compd. 2018;764:10–6.
44. Armijo LM, et al. Antibacterial activity of iron oxide, iron nitride, and tobramycin conjugated nanoparticles against *Pseudomonas aeruginosa* biofilms. Journal of Nanobiotechnology. 2020;18(1):35.

## Figures

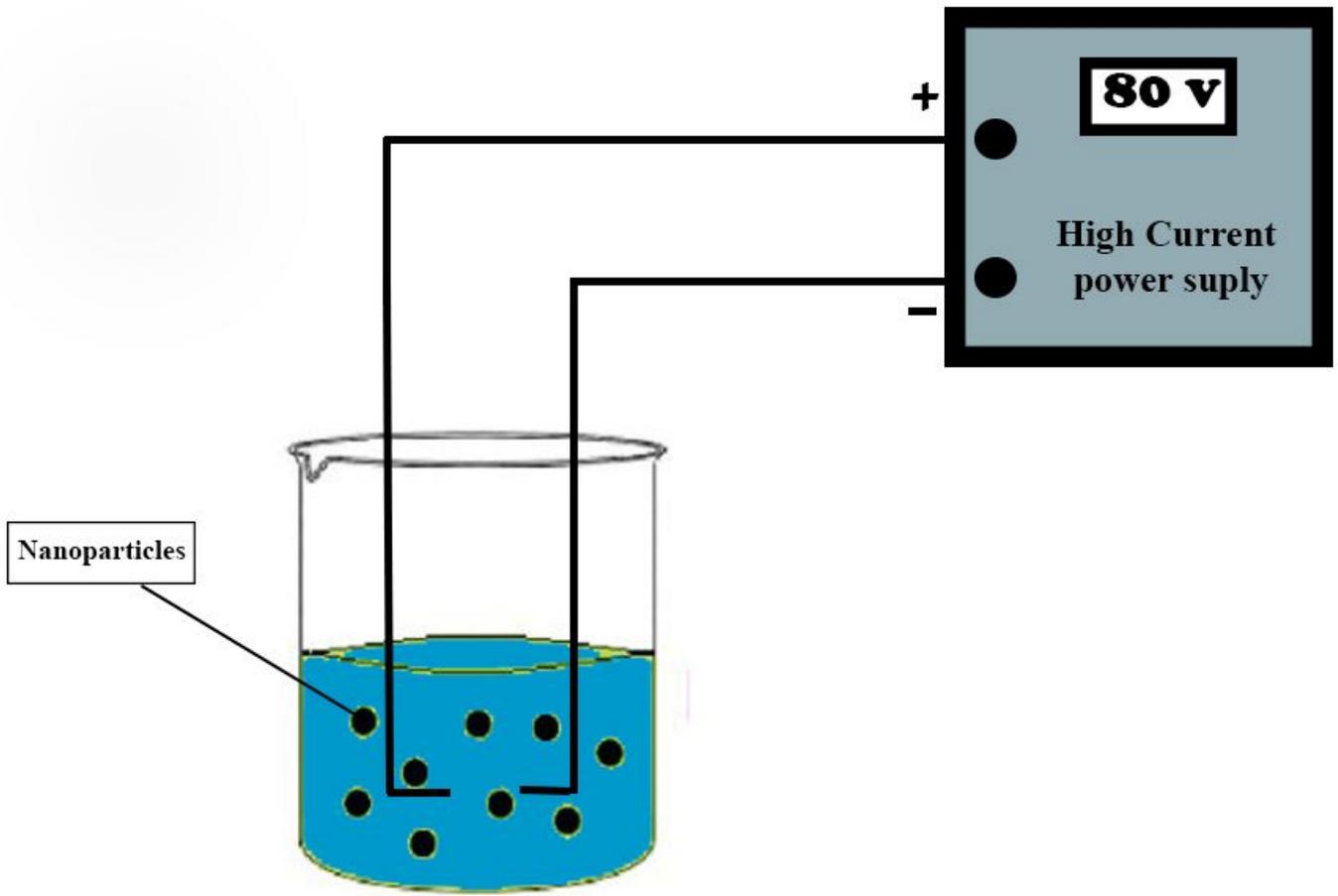


Figure 1

Schematic of electric discharge method process.

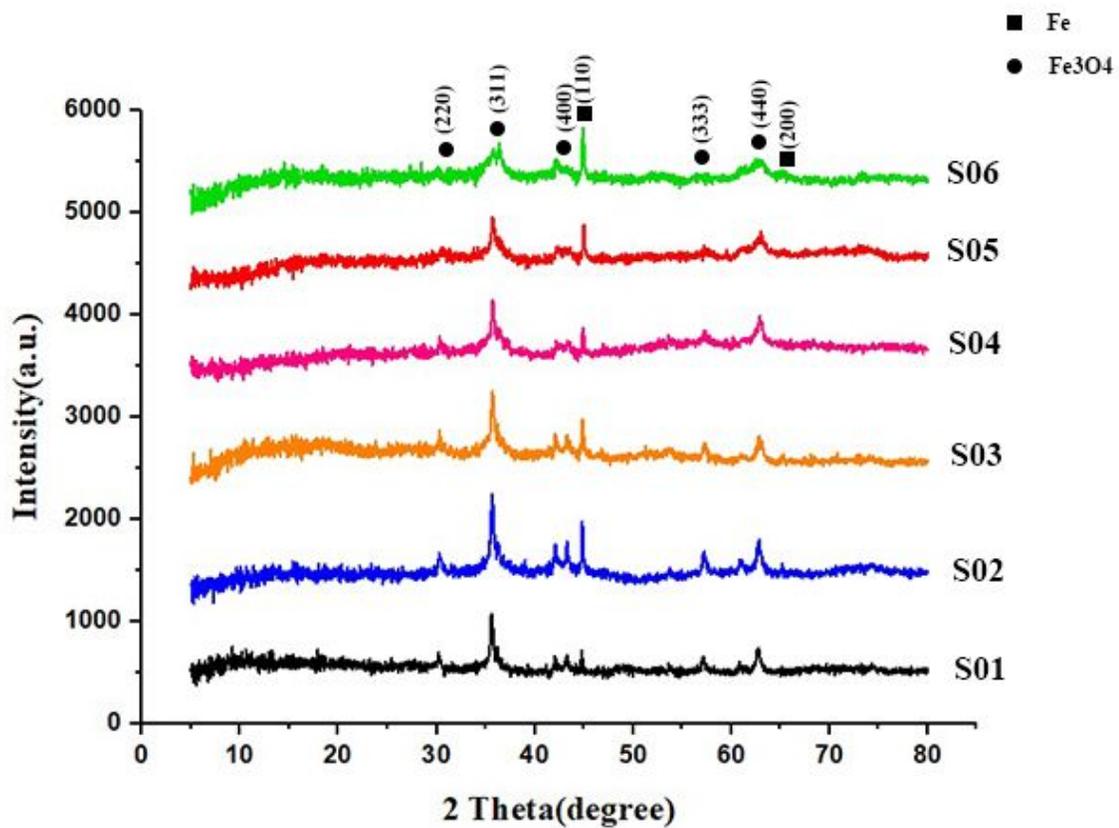


Figure 2

XRD pattern of the iron oxide NPs prepared by the electric discharge in liquid.

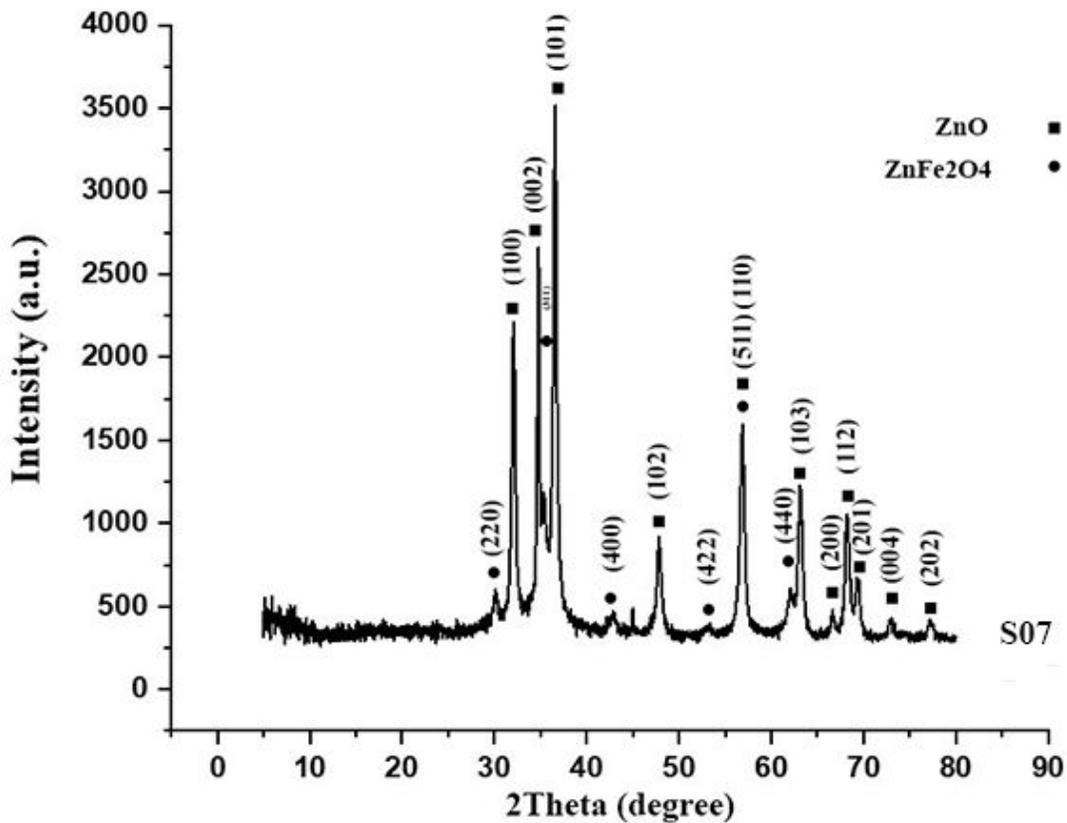


Figure 3

XRD pattern of the Fe-Zn oxide NPs prepared by the electric discharge in liquid.

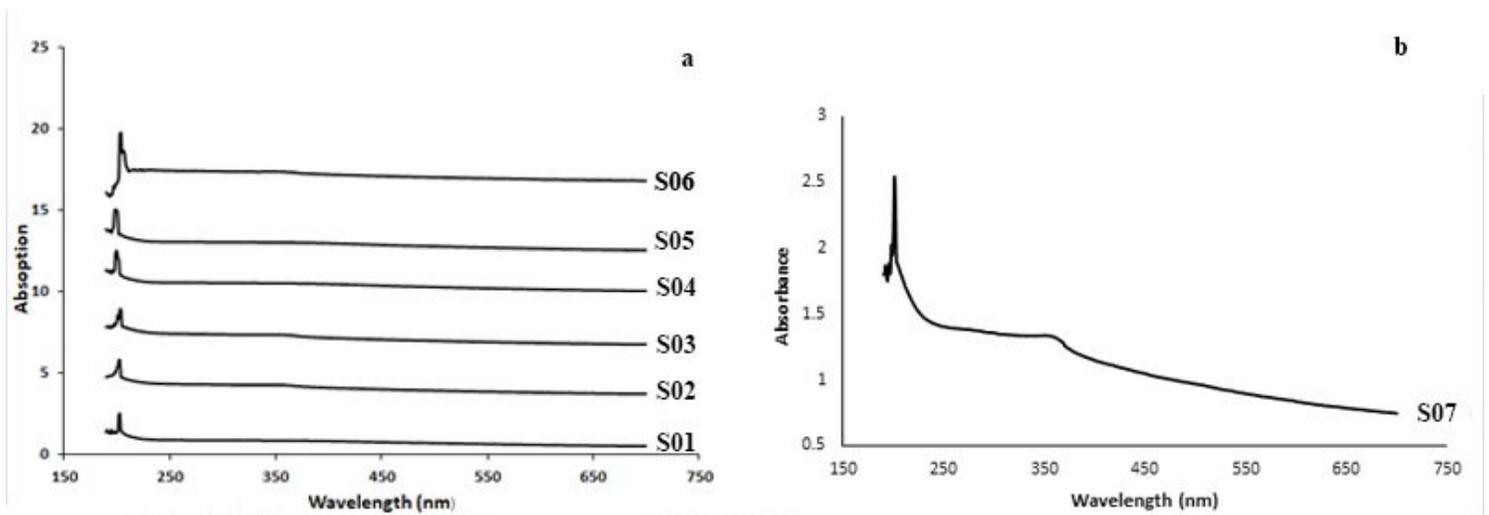
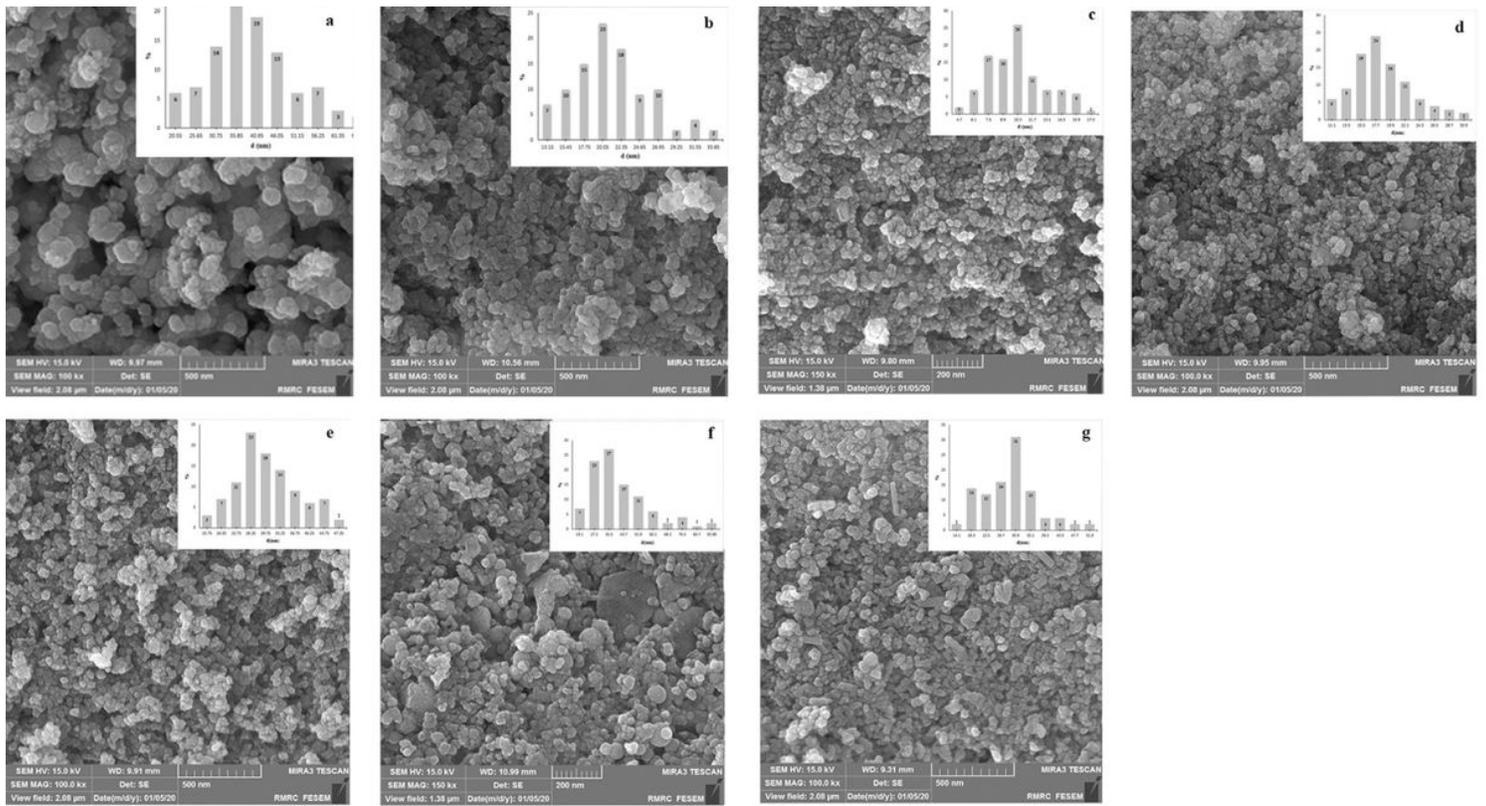


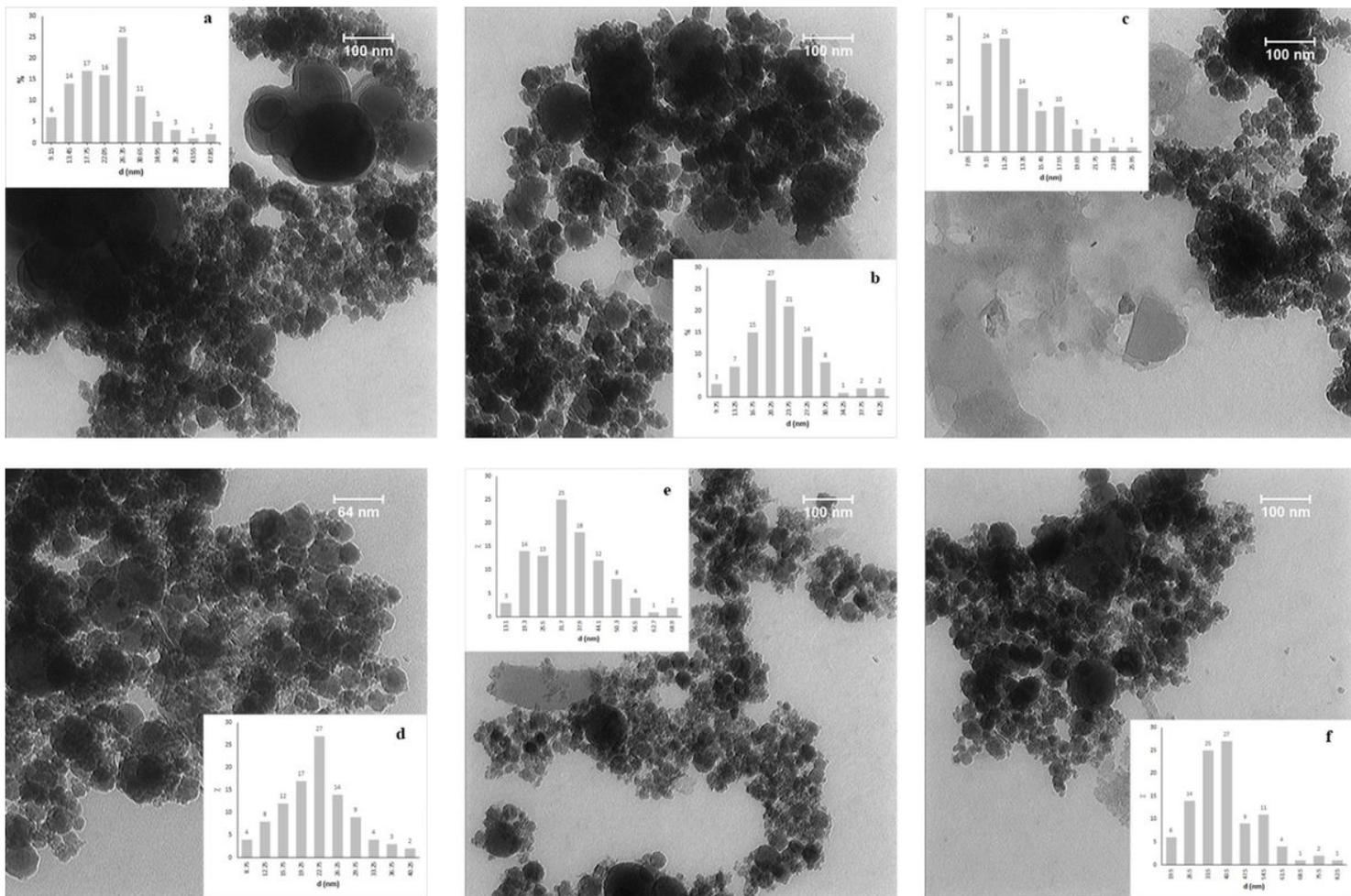
Figure 4

UV-VIS spectra of a) iron oxide nanoparticles and b) Fe-Zn nanoparticles.



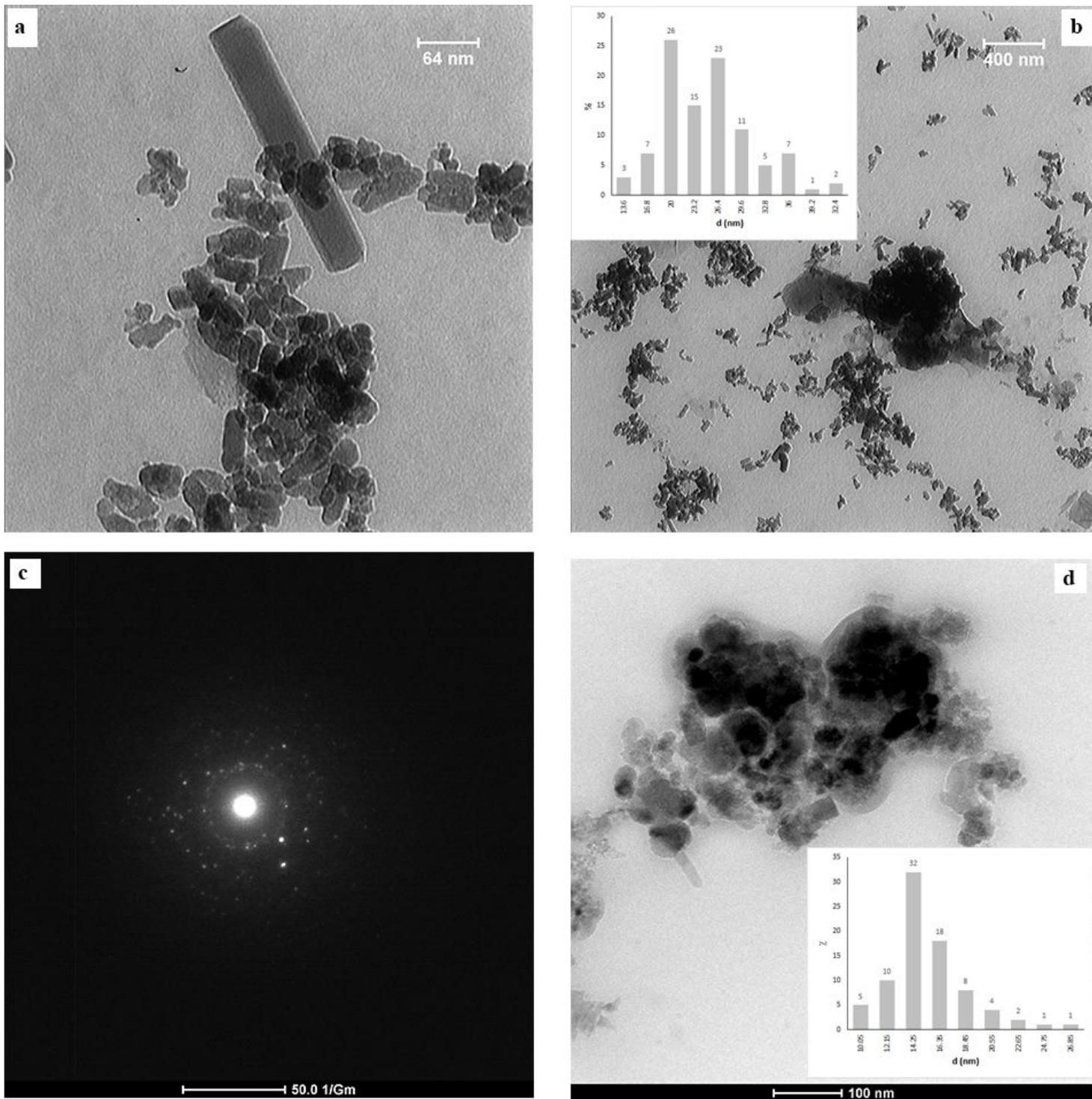
**Figure 5**

FESEM images of: a) S01, b) S02, c) S03, d) S04, e) S05, f) S06 and g) S07 samples.



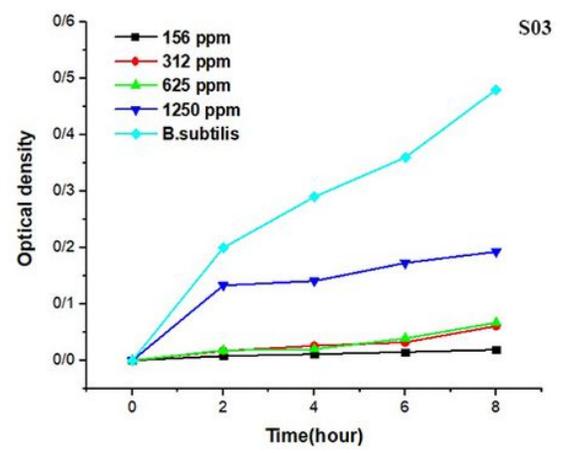
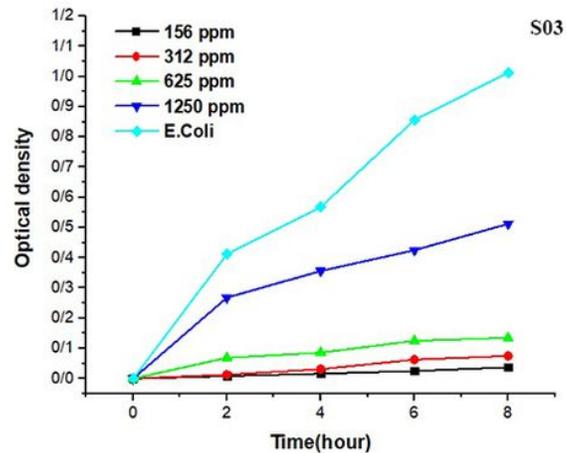
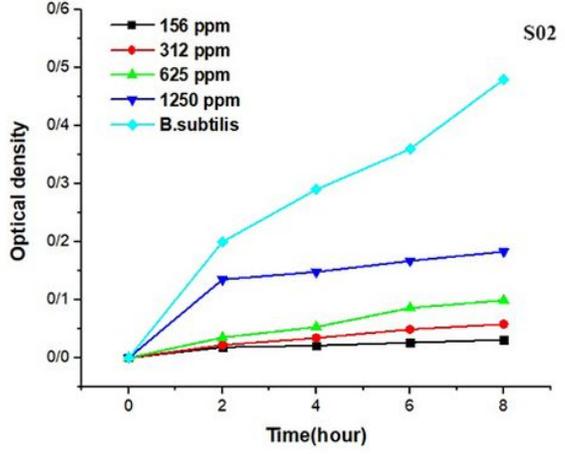
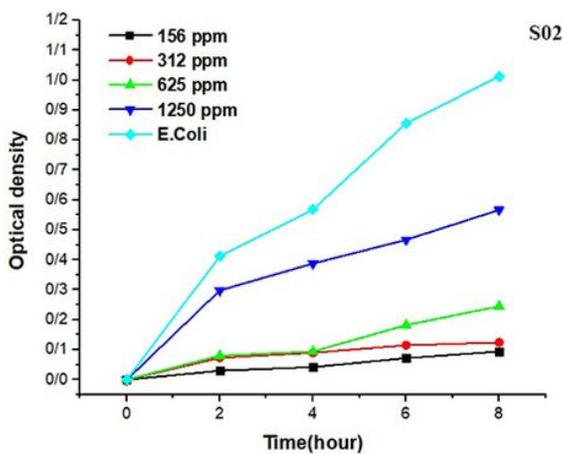
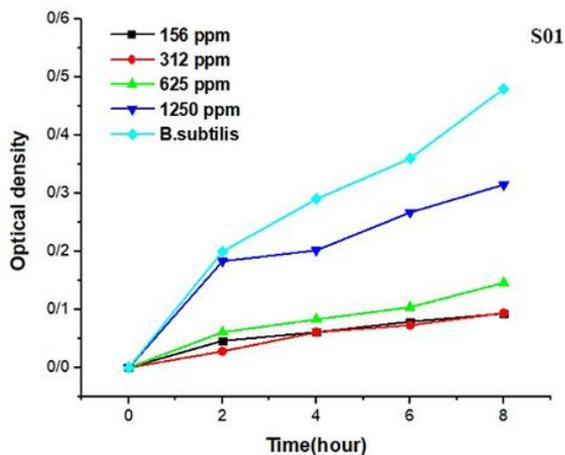
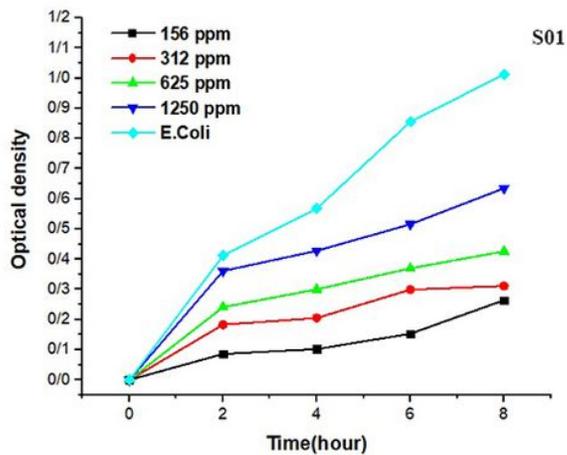
**Figure 6**

TEM images of samples: a)S01, b)S02, c)S03, d)S04, e)S05, f)S06.



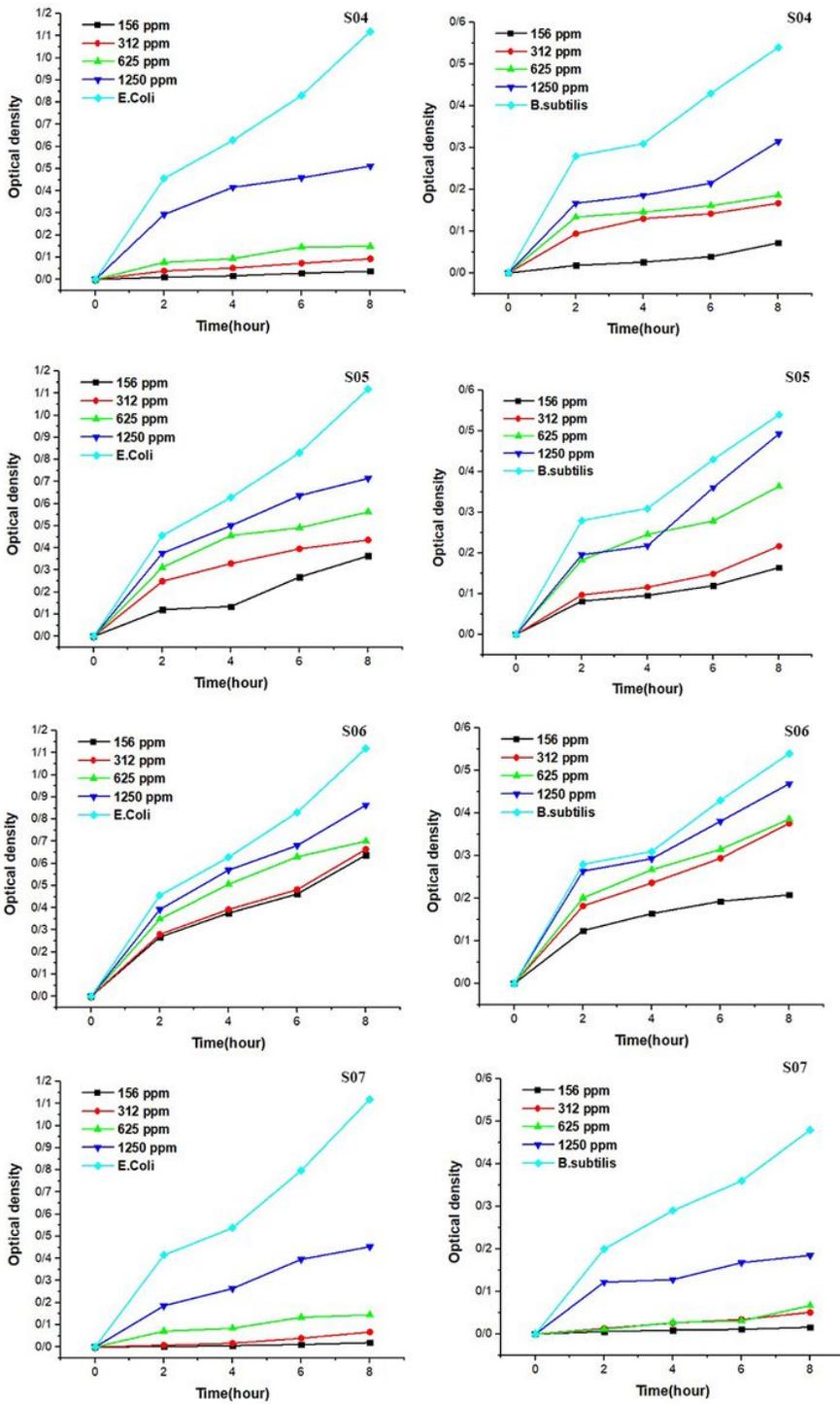
**Figure 7**

a and b) TEM images of Fe-Zn NPs, c) SAED pattern, d) HRTEM image of Fe-Zn NPs.



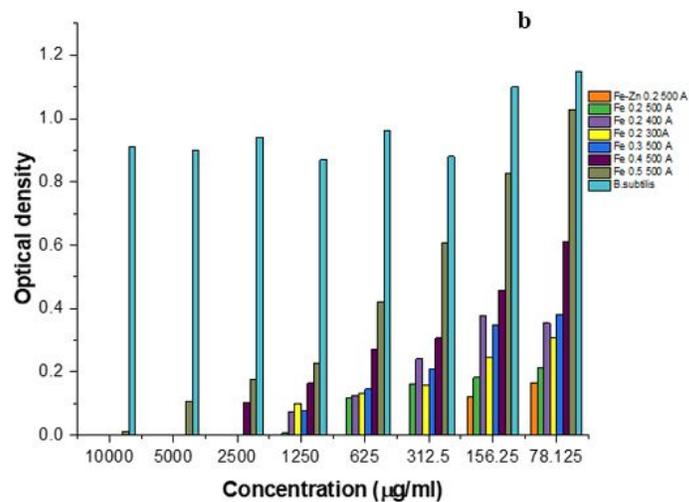
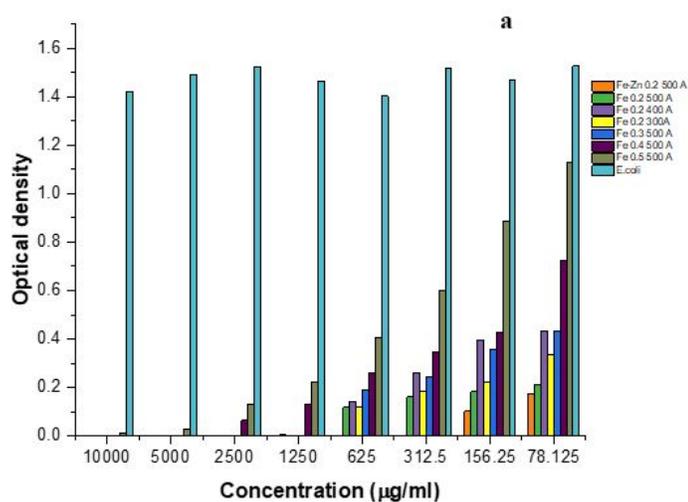
**Figure 8**

Bacterial growth curve in the presence of synthesized nanoparticles.



**Figure 9**

Bacterial growth curves in the presence of synthesized nanoparticles.



**Figure 10**

Graphical results of antibacterial test by MIC method for a)E.Coli, b)B.subtilis.

## Supplementary Files

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- [GA.jpg](#)
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