Magnetic core-shell $\text{Fe}_3\text{O}_4@\text{TiO}_2$ nanocomposites for broad spectrum antibacterial applications

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Abstract
The authors have synthesised a core-shell $\text{Fe}_3\text{O}_4@\text{TiO}_2$ nanocomposite consisting of $\text{Fe}_3\text{O}_4$ as a magnetic core, and $\text{TiO}_2$ as its external shell. The $\text{TiO}_2$ shell is primarily intended for use as a biocompatible and antimicrobial carrier for drug delivery and possible other applications such as wastewater remediation purposes because of its known antibacterial and photocatalytic properties. The magnetic core enables quick and easy concentration and separation of nanoparticles. The magnetite nanoparticles were synthesized by a hydrothermal route using ferric chloride as a single-source precursor. The magnetite nanoparticles were then coated with titanium dioxide using titanium butoxide as a precursor. The core-shell $\text{Fe}_3\text{O}_4@\text{TiO}_2$ nanostructure particles were characterized by XRD, UV spectroscopy, and FT-IR, TEM, and VSM techniques. The saturation magnetization of $\text{Fe}_3\text{O}_4$ nanoparticles was significantly reduced from 74.2 to 13.7 emu/g after the $\text{TiO}_2$ coating. The antibacterial studies of magnetic nanoparticles and the titania-coated magnetic nanocomposite were carried out against gram+ve, and gram–ve bacteria (Staphylococcus aureus, Pseudomonas aeruginosa, Shigella flexneri, Escherichia coli, and Salmonella typhi) using well diffusion technique. The inhibition zone for E. coli (17 mm after 24 h) was higher than the other bacterial strains; nevertheless, both the uncoated and TiO$_2$-coated magnetite nanocomposites showed admirable antibacterial activity against each of the above bacterial strains.

1  |  INTRODUCTION

Metal oxide nanostructured particles are of great significance in the field of antibacterial studies because of large surface areas with extremely active sites. A very discrete type of binary-metal oxide having good magnetization and unique biocompatibility is magnetite ($\text{Fe}_3\text{O}_4$) especially with crystal size on the nanoscale. $\text{Fe}_3\text{O}_4$ nanoparticles have been widely used because of some of its excellent optical and magnetic properties [1–4]. In addition to these, plural cationic oxidation states in $\text{Fe}_3\text{O}_4$ nanoparticles provide an extra edge over other materials for physicochemical applications [5–7]. Various methods have been used by researchers to synthesize high-quality monodisperse magnetic nanoparticles such as chemical co-precipitation, solvothermal, hydrothermal, microemulsion, thermolysis, decomposition of precursors, sol-gel, and polyol methods [8–16]. The agglomeration of crystals is an undesirable occurrence during the synthesis of magnetic nanoparticles. Functionalization and coating of nucleated crystals with ligands can prevent the agglomeration of nanoparticles. Nanoparticles can also have a stronger interaction with the biological cells' surface because of their high surface area to volume ratio compared with bulkier crystals [17]. Some nanoparticles like ZnO, CdSe, TiO$_2$, ZnS, and SiO$_2$ have shown considerable antibacterial/antimicrobial activity, and selective toxicity in biological systems has previously reported [18]. The antibacterial activity of TiO$_2$ has been attributed mainly to its capability to activate free hydroxyl radicals (OH$^-$) under the action of sunlight/ultraviolet radiation [19].

Combining $\text{Fe}_3\text{O}_4$ and $\text{TiO}_2$ nanoparticles to achieve the easy recovery and recycling of TiO$_2$ nanoparticles permits one solution of remediating the contamination of the environment by wastewater. The synthesized nanocomposites could also be easily removed using a magnet after antibacterial application allowing for repeated use of the nanomaterial. The biochemical interaction that occurs between the nanoparticles and the microbes has been attributed to the positive charge on nanoparticles and the negative charge on the outer cell walls of the microbes, which
results in the oxidation of microbes and quick death [20]. Cell lysis mechanism also involves the reaction between the ions generated by nanostructures particles and protein on the bacterial cell [21]. The mechanism of antibacterial action by the nanoparticles thus is also through the oxidative stress due to Reactive Oxygen Species (ROS) that are generated by the nanoparticles [22, 23]. The singlet oxygen produced could also damage the proteins or the DNA in the bacteria and thus lead to the bacteria’s degradation. Kim et al. studied the generation of H$_2$O$_2$, 2.2.1

Iron (III) chloride, NH$_4$Ac (1.5 M), and PVP (0.25 M) were put in 40 ml of ethylene glycol under magnetic stirring. After 3 h of mixing, the solution was shifted into an autoclave for hydrothermal action at 200°C for 20 h. Finally, the autoclave was cooled down, and the black precipitate was taken apart with a magnet. The zone of inhibition was noted in mm [26].

3 | RESULTS AND DISCUSSION
3.1 | XRD characterisation
3.1.1 | Fe$_3$O$_4$ nanoparticles

Figure 1 shows the X-ray diffraction pattern from the magnetite synthesized by the chemical co-precipitation process. These nanoparticles have been investigated using XRD. The XRD chart of magnetite nanostructure particles corresponds to a sequence of peaks at 2θ of 30.1°, 35.5°, 43.2°, 53.4°, 57.2°, and 62.8°, which are associated to the (220), (311), (400), (422), (511), and (440) planes of magnetite, respectively (Crystallography Open Database PDF No. 96-101-1085) [27]. The highly crystalline structure of the magnetite is shown by the sharp peaks of the XRD graph in Figure 1.

3.1.2 | Fe$_3$O$_4$@TiO$_2$ nanoparticles

The XRD graph of these nanocomposites shows peaks at 2θ of 25.3°, 37.8°, 48.2°, that is corresponding to the reflection of (101), (104), and (200) planes of TiO$_2$ nanostructures particles, respectively [28]. Some peaks of Fe$_3$O$_4$ cores and the intense peaks of anatase form of titania are shown in the XRD graph, confirming the presence of TiO$_2$ coating on magnetite nanostructured particles (Figure 2), which reduces the relative peak intensity of the magnetite phase in the diffraction pattern.

3.2 | FTIR
3.2.1 | Fe$_3$O$_4$ nanoparticles

The FTIR spectrum represents hydroxyl group, which is recognized as absorption at 3429 cm$^{-1}$. The band at 2929 cm$^{-1}$ can be attributed to the CH$_2$ stretching bond.
**Figure 1** The X-ray diffraction graph of the chemically synthesized magnetite nanoparticles is shown.

**Figure 2** The X-ray diffraction graph of Fe₃O₄@TiO₂ core-shell nanocomposite is shown here.

**Figure 3** FTIR spectrum of the uncoated Fe₃O₄ nanoparticles is shown here.
The band at 2365 cm\(^{-1}\) is due to CO\(_2\) in the atmosphere. In the spectrum, absorption at 590 cm\(^{-1}\) shows a Fe-O bond. The peak at 1636 cm\(^{-1}\) is reported as an amino group [29] (Figure 3).

### 3.2.2 | Fe\(_3\)O\(_4\)@TiO\(_2\) nanoparticles

The FTIR spectrum showed a band at 3390 cm\(^{-1}\), which is recognized as an O-H bond. The band at 2360 cm\(^{-1}\) is ascribed to the presence of CO\(_2\) in the chamber atmosphere.

The band at 1630 cm\(^{-1}\) is recognized as NH bending. The band at 660 cm\(^{-1}\) is assigned to the Ti-O-Ti stretching vibrations [30] (Figure 4).

### 3.3 | UV characterization

Figure 5 shows the absorption spectrum of magnetite and titania-coated Fe\(_3\)O\(_4\) nanocomposite. When titania nanoparticles were coated on the Fe\(_3\)O\(_4\) nanoparticles, the absorption peak(s) was shifted into the visible region.

### 3.4 | TEM characterization

Both single-phase Fe\(_3\)O\(_4\) nanoparticles and Fe\(_3\)O\(_4\)@TiO\(_2\) core-shell nanostructures, were synthesized using a single precursor by the hydrothermal process. A lot of nanostructured crystalline granules of titania appear to enclose a magnetite core. The titanium dioxide is present as the externally deposited film on the Fe\(_3\)O\(_4\) nanostructure particles, creating the Fe\(_3\)O\(_4\)@TiO\(_2\) nanostructure [31] (Figure 6).

### 3.5 | VSM characterization

The magnetic features of Fe\(_3\)O\(_4\) nanoparticles and Fe\(_3\)O\(_4\)@TiO\(_2\) nanostructure composites have been studied using the VSM technique (Figure 7).

The saturation magnetization (\(M_s\)) of magnetite nanostructure particles and Fe\(_3\)O\(_4\)@TiO\(_2\) nanostructure composites were 74.268 emu/g and 13.755 emu/g, respectively. The saturation magnetization (\(M_s\)) reduced because of the non-magnetic TiO\(_2\) outside film on nanoparticles (Table 1).
3.6 | Antibacterial activities

TiO$_2$-coated magnetite exhibited bactericidal activity in resistance to both gram +ve (positive) and gram -ve (negative) bacteria. The antibacterial activity by the core-shell nano-composite is likely due to the oxidative stress produced by reactive oxygen species (ROS) which include superoxide radical (O$_2^-$), hydroxyl radical (·OH), and also hydrogen peroxide (H$_2$O$_2$) (Figure 8). Collin [32] showed how hydrogen peroxide (H$_2$O$_2$) and other ROS were generated when Fe$^{2+}$/Fe$^{3+}$ reacted with oxygen. The biochemical interaction occurs between H$_2$O$_2$ and membrane proteins or between the substance formed due to magnetite nanoparticles and bacteria’s external bilayer. Then H$_2$O$_2$ enters the outer bilayer of bacteria and destroys them [33]. The various oxidation and reduction
When reactions occur, the Fenton reaction can cause oxidative stress to the cell of bacteria, resulting in the bacterial cell's death. Antimicrobial activity of both 

FeO nanoparticles and FeO@TiO2 nanocomposites against different extracts, that is, P. A. P. aeruginosa, S.T. Shigella flexneri, S.A. Staphylococcus aureus, E. coli.

\[
\begin{align*}
O_2 + e^- & \rightarrow O_2^- + e^- + 2H^+ \rightarrow H_2O_2 + e^- \\
& \rightarrow 2HO\cdot \\
Fe^{3+} + H_2O_2 & \rightarrow Fe^{2+} + HOH^+ + OH\cdot \\
Fe^{3+} + H_2O_2 & \rightarrow Fe^{2+} + HOH^+ + H^+ \\
Fe^{2+} + O_2 & \leftrightarrow Fe^{3+} + O_2^* \\
O_2^* + O_2^* + 2H^+ & \leftrightarrow O_2 + H_2O_2 \\
H_2O_2 + Fe^{2+} & \leftrightarrow OH^+ + HO^- + Fe^{3+} \\
TiO_2 + h\nu & \rightarrow h^+_{VB} + e^-_{CB} \\
H_2O_2 + h^+_{VB} & \rightarrow H + OH^* \\
\end{align*}
\]

OH\cdot and HO2\cdot produced in the reaction are active free radicals. Magnetite (FeO nanoparticles) can slowly oxidize to maghemite (Fe3O4). This oxidation is a critical part of the origin of oxidative stress to the cell of bacteria, resulting in the bacterial cell's death.
negative control and positive control, respectively. The antibacterial actions of both types of the nanoparticles are clearly very significant, with TiO$_2$-coated particles providing superior antibacterial action. The strongest effect was observed on E. coli bacteria for both the types of nanomaterials.

3.6.1 | Antibacterial index of magnetite nanoparticles

The antibacterial index of magnetite nanostructures particles and Fe$_3$O$_4$@TiO$_2$ nanocomposite was shown in Figure 10. The Fe$_3$O$_4$@TiO$_2$ nanocomposite exhibited a better bactericidal activity for E. coli as compared with other bacterial strains.

The magnetite nanoparticles, as core materials, showed good bactericidal activity. The maximum antibacterial activity was observed for TiO$_2$-coated nanoparticles because of its inherent antibacterial properties [37]. The core-shell Fe$_3$O$_4$@TiO$_2$ nanocomposite showed a better antibacterial effect than Fe$_3$O$_4$ nanoparticles. The activity of Fe$_3$O$_4$ nanoparticles to inactivate bacterial strains was improved significantly after coating with TiO$_2$.

The core-shell Fe$_3$O$_4$@TiO$_2$ nanocomposite could be used for drug delivery because of the inherent antibacterial property of TiO$_2$ and the magnetic property of magnetite nanoparticles. The ability to kill cancer cells has also been previously studied [38, 39]. The TiO$_2$ nanoparticles have the capability to both oxidize the pollutants and kill the microorganisms [40]. The antibacterial effect of core-shell Fe$_3$O$_4$@TiO$_2$ nanocomposite was studied, which combined the treatment of microbial contamination and magnetic separation property of magnetite, synthesized. The antibacterial activity of TiO$_2$ nanoparticles using as a shell was better than that reported in previous studies [41, 42].

4 | CONCLUSION

Magnetite superparamagnetic nanostructures particles were fabricated using a single precursor by the hydrothermal method and by using a reducing agent. The Fe$_3$O$_4$ nanostructured particles were coated with titania using a separate hydrothermal process. The effect of the TiO$_2$ shell in the core-shell Fe$_3$O$_4$@TiO$_2$ nanocomposite as a broad-spectrum antibacterial agent was investigated, in comparison to the similar effect of the uncoated core magnetite itself. The antibacterial effects of magnetite core and the titania shell were studied on five bacteria strains: S. aureus, P. aeruginosa, Sibigella flexneri, E. coli, and S. typhi. The Fe$_3$O$_4$@TiO$_2$ nanocomposites showed superior antibacterial action on each bacterium, while the uncoated magnetite’s effect was significantly lesser in comparison. The TiO$_2$-coated magnetite nanoparticles revealed better and more effective antibacterial activity against the E. coli strain of bacteria than the other strains. It can be concluded that Fe$_3$O$_4$@TiO$_2$ is a very active antibacterial agent, as verified by the large diameter of the inhibition zone. The results indicated that nanocomposites synthesized in this work could also be suitable materials for drug delivery applications. These can also be practical and cost-effective agents in cleaning a microbe-polluted water environment where the magnetic core lends itself to easy recycling. The results reveal that bacterial illness could be treated by core-shell Fe$_3$O$_4$@TiO$_2$ nanostructure particles employing TiO$_2$ as a shell due to its inherent antibacterial properties. Fe$_3$O$_4$@TiO$_2$ nanocomposites could be efficient and recyclable antibacterial agents because of their magnetic, anti-bacterial and photocatalytic features.

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