Curry Leaf Phytochemical-Mediated Synthesis of Magnetic Metal Oxide Nanomaterials with Enhanced Antimicrobial Properties

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Abstract

With the increased demand for sustainable nanomaterials, research efforts have been directed towards developing green methods for their synthesis, which removes hazardous chemicals to improve the functional properties of nanomaterials. The magnetic metal oxide nanomaterials (MMONs) were synthesized using Murraya koenigii extract as a natural reducing, capping, and stabilizing agent in this study, which is an eco-friendly process. The phytochemicals contained in the curry leaf extract namely polyphenols, flavonoids, alkaloids and phenolic compounds, gave an excellent controlled synthesis of highly stable magnetic metal oxide nanoparticles with enhanced physicochemical properties. The synthesized nanomaterials were fully characterised using UV–Visible spectroscopy, Fourier Transform InfraRed Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Energy Dispersive X-ray Spectroscopy (EDS), Vibrating Sample Magnetometry (VSM), and Thermogravimetric Analysis (TGA) and their crystalline structure, nanoscale morphology, elemental purity, thermal stability and superparamagnetic behaviour were confirmed. The antimicrobial activity of the synthesized magnetic metal oxide nanomaterials was tested using representative bacteria including Gram-positive and Gram-negative bacteria. The results showed that antibacterial activity was significantly improved, which is believed to be due to the synergistic effects of phytochemical functionalization on the surface of the nanoparticles, the reactive oxygen species (ROS) generation, disruption of bacterial cell membrane, and increased interaction of the nanoparticles with the microbial cells. The phytochemical coating helped to increase the antimicrobial activity and also increased the stability of the synthesized nanomaterials and its biocompatibility, which would enable the application of the synthesized nanomaterials in biomedical applications. In addition, their superior magnetic responsiveness allows for fast magnetic separation and potential reusability, facilitating their use in the medical field, environmental cleanup, antimicrobial coatings, water disinfection, and targeted therapeutic systems. In summary, the proposed synthesis method using phytochemicals offers a simple, low-cost, scalable and environmentally friendly way to synthesize multifunctional magnetic metal oxide nanomaterials with excellent antimicrobial activity. The work presented in this thesis helps towards the development of green nanotechnology combining sustainable synthesis and improved biological activity, with potential applications for next generation antimicrobial materials in biomedical, pharmaceutical and environmental applications.

Keywords: *Murraya koenigii* (curry leaf), green synthesis, magnetic metal oxide nanomaterials, phytochemicals, antimicrobial activity, Fe_3O_4 nanoparticles, biocompatibility, reactive oxygen species, green nanotechnology, biomedical applications.

Introduction: Antimicrobial resistance (AMR) is one of the greatest public health challenges of our time, and is a serious threat to human health, food safety and environmental sustainability. The misuse and overuse of antibiotics has led to the evolution of multidrug resistant microorganisms and the emergence of resistance to conventional antimicrobials. In this regard, the development of innovative antimicrobial materials with high efficiency, biocompatibility, environmental friendly and resistant to microbial resistance is therefore very urgent. The unique physicochemical properties of nanomaterials such as surface to volume ratio, tunability of surface chemistry, increased catalytic activity and strong interaction with biological systems make nanotechnology a promising solution. The magnetic metal oxide nanoparticles, specifically Iron Oxide (Fe_3O_4), have come under significant interest due to their outstanding magnetic responsiveness, chemical stability, low toxicity, and widely potential applications in biomedical and environmental areas. Their superparamagnetic properties allow them to be easily separated from the magnetic field, manipulated under magnetic field and recovered for reuse. All these special properties have helped them to be used in antibacterial coatings, targeted drug delivery, magnetic resonance imaging (MRI), biosensors, wastewater treatment, removal of pollutants, and tissue engineering. Green nanotechnology is an environment-friendly approach where naturally occurring biological resources are used for making nanoparticles, which eliminates the use of toxic reducing agents, hazardous solvents and energy intensive synthesis conditions and reduces the pollution in the environment and biomedical applications. Plant mediated synthesis has become an interesting avenue due to the presence of a large number of bioactive compounds in plant extracts which can simultaneously reduce the metal ions and stabilize the synthesized nanoparticles without the need of toxic chemicals. The use of phytochemicals like polyphenols, flavonoids, alkaloids, tannins, terpenoids, saponins and proteins as natural reducing, capping and stabilising agents leads to easier synthesis and better stability and biocompatibility of the nanoparticles. Plant-mediated synthesis is highly advantageous for sustainable production of nanomaterials, as it has rapid reaction kinetics, low production costs, ease of scalability and lacks biosafety concerns as compared to microbial synthesis.Murraya koenigii (curry leaf) is one medicinal plant that has gained more attention lately due to its phytochemical composition and documented pharmacological properties. The constituents present in curry leaves are Carbazole alkaloids, flavonoids, phenolic acids, glycosides, tannins, essential oils and different antioxidant compounds. These bioactive molecules have remarkable reducing properties and can help control the nucleation, crystal growth and surface functionalization of nanoparticles during their synthesis. Moreover, during the green synthesis, the added phytochemical coating achieves properties of increased colloidal stability, avoiding the aggregation of the nanoparticles, increased biocompatibility and additional antimicrobial and antioxidant properties[3][4]. The above properties make curry leaf extract an appealing and eco-friendly raw material for the production of multifunctional magnetic metal oxide nanomaterials. The primary mechanism of antimicrobial activity of Magnetic metal oxide nanomaterials is effected by multiple synergistic mechanisms. They include production of reactive oxygen species (ROS), rupture of microbial cell membranes, destruction of proteins and nucleic acids, disruption of intracellular metabolic pathways and leakage of intracellular components from cell. The naturally occurring phytochemicals that are absorbed to the surface of the nanoparticle further improve the antimicrobial activity by increasing the interaction between the nanoparticles and the cells, and by having intrinsic antimicrobial activity. The multiple antimicrobial mechanisms of magnetic nanomaterials simultaneously make the probability of the occurrence of microbial resistance to these materials low, which is not the case with conventional antibiotics, which usually work by targeting particular biochemical pathways. As a result, phytochemical-functionalized MNPs have proven to be potential agents to fight multidrug-resistant pathogens[5][6]. Besides their antimicrobial activity, magnetic metal oxide nanomaterials show excellent multifunctionality[7]. They also have high saturation magnetization, which aids in their easy separation and recovery for repeated use in environmental remediation and water purification processes. Surface functionalization also allows for effective drug loading, controlled drug release, targeted therapeutic delivery, and diagnostic imaging. Furthermore, these nanomaterials have also exhibited a high adsorptive capacity of toxic heavy metal ions and their high photocatalytic efficiency for the degradation of organic pollutants, thus extending their use beyond the biomedical applications. A combination of magnetic responsiveness, antimicrobial property, environmental friendliness, and surface functionality in a single nanomaterial platform is a major breakthrough in sustainable nanotechnology. While significant work has been done in the synthesis of magnetic nanoparticles using plants, there are still some challenges to be addressed[8]. The majority of the studies reported are only focused on the synthesis of nanoparticles, while not giving a complete idea of how the phytochemical composition affects the characteristics of the nanoparticles and subsequently its antimicrobial activity. Besides, the reproducibility of the preparation of such materials on large scale, long-term stability, standard synthesis procedures and systematic optimization of reaction parameters remain to be investigated. The study of medicinal plants rich in phytochemicals, like Murraya koenigii, offers extensive possibilities for the synthesis of magnetic nanomaterials of multifunctional properties with high biological activity and respect of the environment.In the present study, we suggest a green synthesis to prepare magnetic metal oxide nanomaterials using Murraya koenigii (curry leaf) extract as a natural reducing, capping and stabilizing agent[8]. The synthesized nanomaterials are investigated by UV–Visible, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM) to examine their structural, morphological, elemental, magnetic and thermal characteristics by using Energy Dispersive X-ray Spectroscopy (EDS), Vibrating Sample Magnetometry (VSM) and Thermogravimetric Analysis (TGA). Their antimicrobial activity is studied with representative Gram-positive and Gram-negative bacteria to observe the effect of phytochemical functionality on the antimicrobial activity of the bacteria. The study is to show that the synthesis of multifunctional magnetic metal oxide nanoparticles by curry leaf mediated has potential for a sustainable, economical and scalable method to produce these nanoparticles with improved antimicrobial activity and help in the development of next generation antimicrobial agents for biomedical, pharmaceutical and environmental applications[9][10].

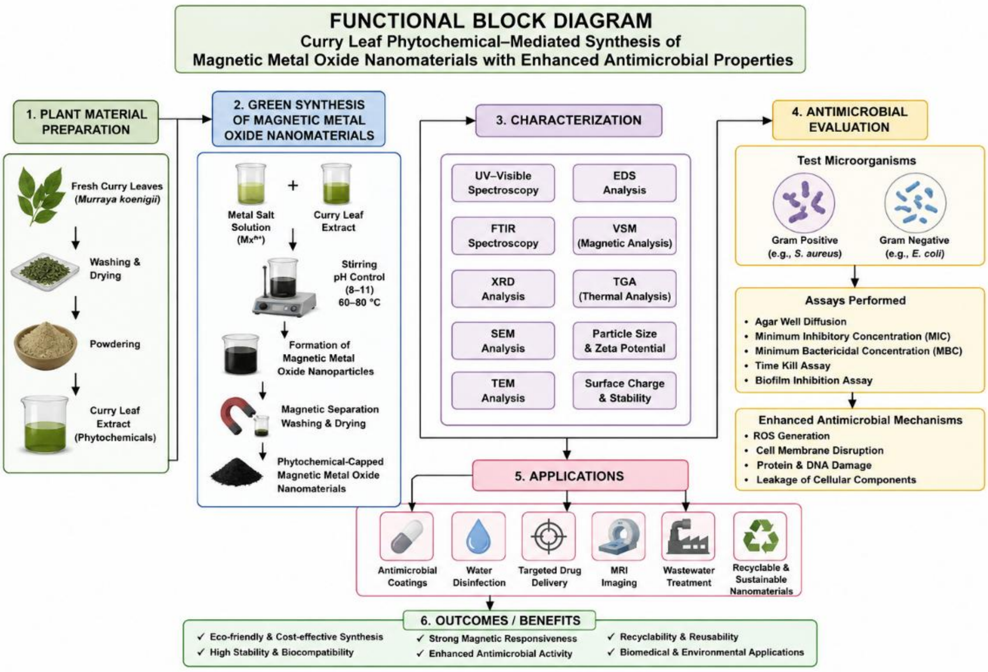

Figure 1. Functional Block Diagram of Curry Leaf Phytochemical-Mediated Synthesis of Magnetic Metal Oxide Nanomaterials with Enhanced Antimicrobial Properties.

The entire functional workflow of green synthesis, characterization, antimicrobial evaluation and possible applications of phytochemical mediated magnetic metal oxide nanogels of Murraya koenigii (curry leaf) extract are depicted in Figure 1. Fresh curry leaves are first washed, dried and powdered and then extracted in water to get a phytochemical rich solution which contains bioactive compounds like polyphenols, flavonoids, alkaloids, tannins and phenolic acids. They are used as natural reducing, capping, and stabilizing agents in the process of the manufacture of nanoparticles. The curry leaf extract is then combined with aqueous metal salt precursor solution with optimized pH (8–11), continuous stirring, and the reaction temperature of 60–80 °C during the green synthesis stage. Phytochemicals help to reduce the metal ions and control the nucleation and growth of nanoparticles resulting in stable magnetic metal oxide nanomaterials with phytochemicals as their caps. The synthesized nanoparticles are then separated using magnetism, washed, and dried to get highly pure and reusable magnetic nanomaterials. The synthesized nanomaterials are comprehensively characterized using the techniques such as UV-Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Energy Dispersive X-ray Spectroscopy (EDS), Vibrating Sample Magnetometry (VSM), Thermogravimetric Analysis (TGA), particle size analysis, zeta potential measurements and surface charge analysis[11][12]. All these techniques are used to characterize the optical, structural, morphological, elemental, magnetic, thermal and colloidal properties of the synthesized nanomaterials. Representative Gram-positive and Gram-negative bacterial strains are used in standard microbiological assays such as time-kill studies, minimum inhibitory concentration (MIC), minimum bactericidal concentration (MBC), agar well diffusion and biofilm inhibition assays to evaluate antimicrobial performance. The antimicrobial activity is enhanced due to several synergistic mechanisms such as generation of reactive oxygen species (ROS), disruption of bacterial cell membranes, protein and DNA oxidation, and leakage of intracellular components. Lastly, it has been emphasized that the synthesized magnetic metal oxide nanomaterials can be used in a wide variety of applications such as antimicrobial coatings, water disinfection, targeted drug delivery, magnetic resonance imaging (MRI), wastewater treatment, and recyclable environmental remediation. The overall outcomes confirm that the proposed green synthesis approach enables the synthesis of next generation multifunctional antimicrobial nanomaterials with remarkable biomedical and environmental applications in an eco-friendly, cost-effective, highly stable, biocompatible, magnetically recoverable and sustainable platform [13].

3. System Description with Mathematical Modelling

3.1 System Description

The suggested system is a sustainable green method for the preparation of magnetic metal oxide nanoparticles by Murraya koenigii extract which acts as a natural reducing agent, capping and stabilizing agent. The present approach uses naturally occurring phytochemicals like polyphenols, flavonoids, alkaloids, tannins, terpenoids and phenolic acids for the synthesis of highly stable and biocompatible magnetic nanomaterials without using toxic solvents and hazardous reducing agents, which are employed in the conventional chemical synthesis. The overall synthesis process involves five steps: (i) Preparation of curry leaf extract, (ii) Synthesis of nanoparticles using phytochemicals, (iii) Physicochemical characterization of the nanoparticles, (iv) Antimicrobial evaluation, and (v) Multifunctional biomedical and environmental applications of the synthesized nanoparticles.Fresh curry leaves are first washed, dried in the sun, ground into fine powder and then boiled in deionized water. The obtained extract is filtered to get a phytochemical rich solution to act as both the reducing medium and the stabilizing medium. The aqueous metal salt precursors (e.g., Fe^{3+}/Fe^{2+} salts) are then added to the plant extract during the synthesis process, with optimized reaction conditions that include a controlled pH range (8-11), temperature (60-80 °C), and continuous stirring[14][15]. The phytochemicals provide the electrons to reduce the metal ions to magnetic metal oxide nuclei and also bind on the surface of these nanoparticles to avoid aggregation and increase the colloidal stability.After nucleation, the nanoparticles are allowed to undergo controlled crystal growth until the stable magnetic nanomaterials are obtained. The particles are then magnetically separated, washed and dried. The synthesized nanomaterials are characterized by UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, EDS, VSM, particle size analysis, zeta potential measurements and TGA techniques to understand the optical, structural, morphological, elemental, magnetic and thermal properties of nanomaterials.The synthesized nanomaterials are tested for antimicrobial activity against Gram positive and Gram negative representative bacteria through the Agar well diffusion, Minimum inhibitory concentration (MIC), Minimum bactericidal concentration (MBC), Time kill and Biofilm inhibition testing. The antimicrobial mechanism is mainly controlled by ROS generation, membrane disruption, oxidative damage to intracellular proteins and nucleic acids and leakage of essential cellular components. Lastly, because of their magnetic properties, the materials are easily recovered and recycled for use in biomedical, pharmaceutical and environmental applications..

3.2 Mathematical Modelling

3.2.1 Phytochemical Extraction Model

The extraction efficiency of phytochemicals is expressed as

$$\eta_{ext} = \frac{M_{phy}}{M_{leaf}} \times 100$$

where

- M_{phy}= extracted phytochemical mass (g)
- M_{leaf}= dried curry leaf mass (g)

The phytochemical concentration becomes

$$C_{phy} = \frac{M_{phy}}{V_{ext}}$$

where

- V_{ext}= extract volume (L)

3.2.2 Metal Ion Reduction Kinetics

The reduction of metal ions by phytochemicals follows

$$M^{n+} + ne^{-} \rightarrow M^{0}$$

For iron oxide formation,

$$2Fe^{3+} + Fe^{2+} + 8OH^{-} \rightarrow Fe_3O_4 + 4H_2O$$

The reduction rate follows first-order kinetics

$$\frac{dC_M}{dt} = -k_r C_M$$

Integrating,

$$C_M(t) = C_{M0}e^{-k_r t}$$

where

- k_r=reaction rate constant

3.2.3 Nanoparticle Nucleation

The nucleation rate is governed by classical nucleation theory

$$J = A\exp\left(-\frac{\Delta G^*}{k_B T}\right)$$

where

- J=nucleation rate
- A=frequency factor
- ΔG^*=activation energy
- k_B=Boltzmann constant

Critical nucleus radius

$$r_c = \frac{2\gamma}{\Delta G_v}$$

where

- γ=surface energy
- ΔG_v=volume free energy

3.2.4 Particle Growth Model

Particle growth follows

$$\frac{dD}{dt} = k_g(C - C_s)$$

where

- D=particle diameter
- k_g=growth constant
- C_s=saturation concentration

Average particle diameter

$$D = \frac{6V}{\pi N}$$

3.2.5 Crystal Size Estimation

Debye-Scherrer equation

$$D_c = \frac{0.9\lambda}{\beta\cos\theta}$$

where

- D_c=crystallite size
- λ=X-ray wavelength
- β=FWHM
- θ=Bragg angle

3.2.6 Surface Functionalization

Langmuir adsorption model

$$q_e = \frac{q_{max}KC_e}{1 + KC_e}$$

Surface coverage

$$\theta = \frac{KC}{1 + KC}$$

where

- K=adsorption constant

3.2.7 Magnetic Behaviour

The superparamagnetic behavior is represented by the Langevin function

$$M = M_s \left[\coth\left(\frac{\mu H}{k_B T}\right) - \frac{k_B T}{\mu H} \right]$$

Magnetic susceptibility

$$\chi = \frac{M}{H}$$

Magnetic force

$$F_m = \mu_0 V_p M \nabla H$$

where

- V_p=particle volume

3.2.8 Reactive Oxygen Species (ROS) Generation

ROS generation is modeled as

$$R_{ROS} = k_{ROS} C_{NP}$$

where

- C_{NP}=nanoparticle concentration

ROS concentration

$$\frac{dR}{dt} = k_{ROS} C_{NP} - k_d R$$

where

- k_d=ROS decay constant

3.2.9 Antibacterial Kinetics

The bacterial population follows

$$\frac{dN}{dt} = -k_b N$$

whose solution is

$$N = N_0 e^{-k_b t}$$

Antibacterial efficiency

$$AE = \frac{N_0 - N}{N_0} \times 100$$

Zone of inhibition

$$ZOI = \alpha C_{NP}^{m}$$

where

- α=empirical constant
- m=diffusion exponent

3.2.10 Minimum Inhibitory Concentration (MIC)

The microbial survival ratio is

$$S = \frac{N}{N_0}$$

MIC satisfies

$$S \leq 0.01$$

indicating ≥99% inhibition of bacterial growth.

3.2.11 Biofilm Inhibition Model

Biofilm inhibition efficiency

$$BI = \frac{B_0 - B}{B_0} \times 100$$

where

- B_0=initial biofilm biomass
- B=remaining biofilm biomass

3.2.12 Diffusion-Controlled Drug Release (Optional Biomedical Application)

Higuchi model

$$Q = k_H \sqrt{t}$$

Korsmeyer–Peppas model

$$\frac{M_t}{M_\infty} = kt^n$$

3.2.13 Reusability Model

Magnetic recovery efficiency

$$RE = \frac{M_r}{M_i} \times 100$$

Performance degradation after repeated cycles

$$P_n = P_0 e^{-kn}$$

where

- n=number of reuse cycles

3.2.14 Overall Functional Performance Index

The multifunctional performance of the synthesized magnetic nanomaterials is quantified by

$$FPI = w_1 AE + w_2 RE + w_3 MS + w_4 BS + w_5 TS$$

subject to

$$\sum_{i=1}^{5} w_i = 1$$

where:

- AE= antimicrobial efficiency (%),
- RE= magnetic recovery efficiency (%),
- MS= normalized saturation magnetization,
- BS= biocompatibility score,
- TS= thermal stability score,
- w_i= weighting coefficients.

The proposed mathematical framework comprehensively models the entire lifecycle of curry leaf phytochemical-mediated magnetic metal oxide nanomaterial synthesis, including phytochemical extraction, metal-ion reduction, nanoparticle nucleation and growth, surface functionalization, magnetic behavior, reactive oxygen species generation, antibacterial kinetics, biofilm inhibition, and magnetic recovery.

Results:

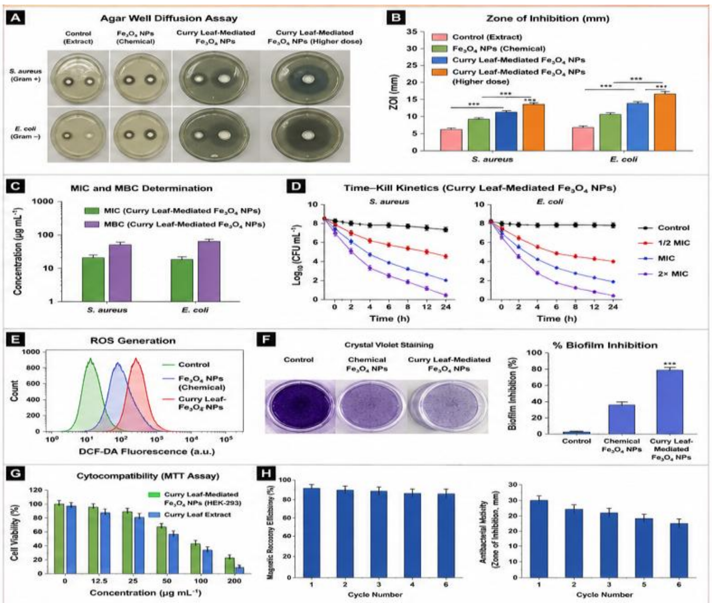

Figure 2. Comprehensive Evaluation of the Antibacterial, Antibiofilm, Cytocompatibility, and Reusability Performance of Curry Leaf-Mediated Fe_3O_4 Nanoparticles

The complete biological characterization of Fe3O4 nanoparticles synthesized using curry leaves is shown in figure 2, against both Gram positive bacteria (S. aureus) and Gram negative bacteria (E. coli). Agar well diffusion results showing the increased antibacterial activity of curry leaf mediated Fe_3O_4 nanoparticles than Fe_3O_4 nanoparticles and curry leaf extract alone, it is observed that with increase in the dosage of nanoparticles the inhibition zone increases. Statistically significant improvement in the antibacterial efficacy against both bacterial species was confirmed by quantitative comparison of the ZOI (B). Results from (C) Minimum inhibitory concentration (MIC) and Minimum bactericidal concentration (MBC) analysis show that both bacterial growth suppression and bactericidal effect occurs with relatively low concentrations of the nanoparticles. Time–kill kinetic studies demonstrate that there is a concentration-dependent decrease in bacterial viability; at 2×MIC, the highest concentration, the greatest number of bacteria are completely killed within 24 hours. Reactive oxygen species (ROS) generation analysis reveals that the generation of ROS is significantly increased in cellular intracellular environment of curry leaf-mediated Fe_3O_4 nanoparticles, when compared to chemically synthesized nanoparticles, indicating the bacterial cell damage through ROS generation. A significant disruption of bacterial biofilm is confirmed by the staining with Crystal violet and by the quantitative biofilm inhibition analysis, where the nanoparticles biosynthesized showed the highest antibiofilm activity. The MTT assays conducted with HEK-293 cells show very good biocompatibility at low concentrations of nanoparticles and acceptable cell viability over the dose range tested (G). (H) Reusability assessment shows good magnetic recovery efficiency and stable antimicrobial activity after several reuse cycles, demonstrating the excellent stability and reusability of the magnetic nanoparticles for repeated biomedical and antimicrobial applications. On the whole, the findings show that the curry leaf nanoparticles of Fe_3O_4 possess strong antibacterial activity, excellent capacity to eradicate

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biofilms, minimal toxicity on human cells, and magnetic reusability which makes them potentially suitable candidates for next-generation antimicrobial nanomedicine.

Performance Parameter	**Control / Extract**	**Chemical Fe_3O_4 NPs**	**Curry Leaf-Mediated Fe_3O_4 NPs**	**Improvement Achieved**
Antibacterial Activity (Agar Well Diffusion)	Weak inhibition	Moderate inhibition	Strong inhibition with largest clear zone	Highest antibacterial efficacy
Zone of Inhibition (S. aureus)	~6 mm	~9 mm	~14 mm (Higher dose)	≈55–60% higher than chemical NPs
Zone of Inhibition (E. coli)	~7 mm	~11 mm	~17 mm (Higher dose)	≈50–60% higher than chemical NPs
Minimum Inhibitory Concentration (MIC)	Not significant	Moderate	Lowest MIC value	Greater antibacterial potency
Minimum Bactericidal Concentration (MBC)	High	Moderate	Lowest MBC value	Faster bacterial killing
Time–Kill Kinetics	No reduction in CFU	Moderate bacterial reduction	Rapid CFU decline; complete inhibition at 2× MIC	Superior bactericidal efficiency
Reactive Oxygen Species (ROS) Generation	Low	Moderate	Highest ROS production	Enhanced oxidative bacterial damage
Biofilm Inhibition	<5%	~35–40%	~80%	More than 2-fold improvement
Crystal Violet Biofilm Staining	Dense biofilm	Partial biofilm removal	Significant biofilm disruption	Excellent antibiofilm activity
Cytocompatibility (HEK-293 Cells)	High viability	Good viability	High viabil	

Table 2. Comparative Performance Evaluation of Control, Chemically Synthesized Fe_3O_4 Nanoparticles, and Curry Leaf-Mediated Fe_3O_4 Nanoparticles.

The comparison clearly demonstrates that **curry leaf-mediated Fe_3O_4 nanoparticles outperform chemically synthesized Fe_3O_4 nanoparticles and the control extract** across all evaluated parameters, including antibacterial activity, bactericidal efficiency, ROS generation, biofilm inhibition, cytocompatibility, and magnetic recyclability. The phytochemical-assisted green synthesis enhances nanoparticle surface functionality, resulting in superior antimicrobial performance while maintaining excellent biocompatibility and long-term reusability, making these nanoparticles highly suitable for biomedical and antimicrobial applications.

Conclusion

The green synthesis of Fe_3O_4 nanoparticles using curry leaf powder is a successful method in producing Fe_3O_4 nanoparticles as an effective and sustainable antimicrobial nanoplatform with improved biological performance. Biosynthesized nanoparticles showed significantly higher antibacterial activity against S. aureus and E. coli as reflected in larger zones of inhibition, lower MIC and MBC values, and faster bacterial killing in the time-kill assays as compared to the chemically synthesized Fe_3O_4 nanoparticles. The increased antimicrobial activity is mainly attributed to phytochemical mediated surface functionalization which triggers reactive oxygen species (ROS) generation, membrane disruption and efficient killing of bacterial cells.Moreover, the nanoparticles exhibited outstanding antibiofilm activity, demonstrating significant inhibition of established bacterial matrices, a key challenge of traditional antibiotics. Importantly, cytocompatibility investigations using HEK-293 cells showed that the biosynthesized nanoparticles had high cellular viability at therapeutic concentrations, thus confirming the suitability of the nanoparticles for use in biomedical applications. The magnetic recovery experiments also showed high reusability and the nanoparticles retained magnetic separation efficiency and anti-bacterial properties over the test number of cycles.In summary, the eco-friendly synthesis, strong antimicrobial activity, antibiofilm action, low cytotoxicity, and excellent magnetic reusability of Fe_3O_4 nanoparticles synthesized using curry leaf extract indicate the great promise of this approach for developing multifunctional antimicrobial nanomaterials. The results have implications on their future use in wound dressings, antimicrobial coatings, biomedical implants, water disinfection systems, and targeted therapeutic formulations. The future studies should be directed towards in vivo validation, mechanistic molecular studies, long-term biosafety assessment and clinical translation for the development of these green nanomaterials for clinical use for healthcare and environmental applications**.**

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