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PHYTOGENIC GREEN SYNTHESIS OF MULTIFUNCTIONAL MAGNETIC NANOCOMPOSITES FOR BIOMEDICAL, CATALYTIC, AND ENVIRONMENTAL APPLICATIONS

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Abstract

As the demand for sustainable productions of nanomaterials grows, the development of environmentally friendly methods that reduce or completely remove the use of harmful chemicals and improve the functionality of the materials is accelerating. The current study introduces a green synthesis approach for the preparation of multifunctional magnetic nanocomposites through the natural reducing, stabilizing and capping agent Murraya koenigii (curry leaf) extract. Phytochemicals such as polyphenols, flavonoids, alkaloids, and terpenoids found in the extract play a role in the dispersion of magnetic nanoparticles to form uniformly distributed particles with improved physicochemical stability. The structural, morphological, magnetic, elemental and thermal properties of the synthesized nanocomposites were comprehensively assessed by performing various characterization 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 (EDX), Vibrating Sample Magnetometry (VSM) and Thermogravimetric Analysis (TGA). The composites developed are investigated for their multifunctional use in biomedical and environmental applications. Through a series of biomedical studies, the researchers found that the compounds exhibited strong antioxidant properties, high efficacy against Gram-positive and Gram-negative bacteria strains, good biocompatibility, and improved drug-loading potential, all of which suggest their application in targeted drug delivery, fabrication of antimicrobial coatings, and biomedical diagnostics. The environmental studies showed excellent photocatalytic degradation ability for organic dye pollutants, high adsorption ability toward heavy metal ions, and excellent magnetic recoverability for repeated use without much loss of catalytic activity. The magnetic properties enable the nanocomposites to be easily separated from aqueous media, thus enhancing the operational efficiency and reducing secondary contamination. The outcomes reveal that curry leaf extract could be used as a very efficient, renewable and environmentally friendly precursor for the preparation of magnetic nanocomposites of high performance which possess high stability and multifunctionality. The green chemistry approach combined with magnetic nanotechnology offers a platform for the development of sustainable materials for advanced biomedical therapies, environmental remediation, wastewater treatment, and catalytic applications at a lower cost and at a larger scale. This work points out the high potential applications of magnetic nanocomposites of plants as new multifunctional materials, which can be used for solving health and environmental problems and for sustainable nanomanufacturing methods.

Keywords: Green synthesis; Magnetic nanocomposites; Curry leaf extract (*Murraya koenigii*); Biomedical applications; Environmental remediation; Photocatalysis; Heavy metal adsorption; Antibacterial activity; Sustainable nanotechnology.

Introduction

Nanotechnology is a field of science that has revolutionized many other areas and is now one of the most promising solutions to many of the challenges facing the healthcare, environmental protection, energy, and industrial manufacturing sectors. Magneto-composites are among the different classes of nanomaterials that have gained much attention due to the unique property they show when they are incorporated in a composite. These materials have extremely high surface area-to-volume ratio, superparamagnetic properties, good chemical stability and adjustable physicochemical properties, which make them very appropriate for multifunctional applications. Specifically, magnetic nanocomposites prepared from iron oxide nanoparticles have shown tremendous potential in biomedical applications including targeted drug delivery, magnetic resonance imaging (MRI), biosensing, hyperthermia therapy, tissue engineering, and antimicrobial applications. At the same time, they possess excellent adsorption properties, photocatalytic properties and magnetic recovery properties, and are widely used in environmental treatment, wastewater treatment, heavy metal removal and degradation of persistent organic pollutants[1][2]. The combination of magnetic properties and multifunctional surface properties has thus made magnetic nanocomposites attractive materials for next generation biomedical and environmental technologies. In traditional methods, magnetic nanoparticles are prepared by physical and chemical processes like co-precipitation, hydrothermal synthesis, sol-gel process, thermal decomposition, microemulsion process and chemical vapor deposition method. These methods offer very good control of particle size and crystallinity however, they generally involve high temperatures, high pressures, toxic reducing agents, organic solvents and expensive reaction conditions[3][4]. Furthermore, the use of toxic chemicals produces harmful by-products which affect the environment and concerns exist about the biocompatibility and long term toxicity of the engineered nanoparticles, particularly in biomedical applications. Cytotoxicity, oxidative stress, and environmental contamination can be caused by the residual toxic reagents that are attached to the surface of the nanoparticles. In view of the growing importance of sustainable development and green chemistry around the world, researchers have been keen to find synthesis routes that are environmentally friendly and that produce high-quality nanomaterials without sacrificing their functional performance[5][6]. Green synthesis is a viable alternative which utilizes biological resources such as plant extracts, microorganisms, fungi, algae and natural biomolecules to synthesize nanoparticles in mild reaction conditions without using toxic chemicals. The synthesis using plants has some advantages over conventional synthetic methods: it is simple; it has a lower production cost; it can be scaled up; it is less energy intensive; it avoids the use of dangerous chemicals; and it is more biocompatible. Phytochemicals like flavonoids, phenolic acids, alkaloids, tannins, terpenoids, saponins, proteins, amino acids and carbohydrates, which play multipurpose role as reducing, stabilizing and capping agent during the process of nanoparticle formation are naturally present in plant extract. With no need of extra chemical surfactants, these biomolecules control nucleation and crystal growth, inhibit particle agglomeration and stabilize nanoparticles. Therefore, exploiting green synthesis as a viable and green approach to obtain multi-functional nanomaterials for biomedical and environmental applications is attractive[7][8]. Various medicinal plants have been investigated for green nanotechnology of which Murraya koenigii (curry leaf) has been gaining more attention due to its exceptional phytochemical composition and well documented therapeutic properties. Curry leaves are a popular crop in South Asia and are used extensively in traditional Ayurvedic medicine for centuries. The leaves are rich in carbazole alkaloids, flavonoids, polyphenols, glycosides, terpenoids, essential oils, vitamins and antioxidants with antimicrobial, anti-inflammatory, anticancer, antidiabetic, hepatoprotective, cardioprotective and antioxidant activities[9][10]. Naturally occurring bioactive compounds are very good reducing agents that will help in the fast reduction of metal ions into stable nanoparticles and also act as efficient capping agents. The presence of multiple functional groups such as hydroxyl, carbonyl, amino, carboxyl groups further stabilize the nanoparticles by functionalization increasing their dispersion, colloidal stability and biological compatibility. The above characteristics render curry leaf extract as a promising natural source to prepare multifunctional magnetic nanocomposites with sustainable method. The magnetic nanocomposites, which are prepared using the plant extracts have several desirable properties over the chemically synthesized counterpart. Biological molecules attached to the surface of nanoparticles greatly increase the stability of the particles, thus inhibiting their aggregation, increasing dispersibility in water, and lowering cytotoxicity. Additionally, biofunctionalized magnetic nanoparticles display higher biological membrane, microorganism and environment contaminant interactions due to the presence of functional groups that occur in nature. This is a multifunctional behaviour that greatly widens their scope of application in the various branches of science. The magnetic core facilitates separation and recovery with magnetic fields and the bioactive nature of the surface chemistry allows for high levels of catalytic activity, adsorption and biological interactions. Thus, magnetic nanocomposites synthesized using a green approach have emerged as very promising candidates for multifunctional biomedical diagnostics, therapeutic systems, biosensors, antimicrobial coatings, pollutant degradation and water purification technologies[11]. Magnetic Nanocomposites have been identified as one of the most promising applications in the biomedical field due to its unique properties of being both magnetic and biologically useful. Under external magnetic field, superparamagnetic nanoparticles can be finely controlled and targeted delivery of drugs to diseased tissues can be achieved, thereby reducing systemic toxicity and enhancing therapeutic effect. Controlled drug delivery, molecular imaging, biosensing, and magnetic hyperthermia treatment of cancer is further enabled by surface-functionalized magnetic nanoparticles. Further, the natural anti-microbial properties that phytochemicals provide to the nano particles, makes them more effective against pathogenic microorganisms and help to minimize the emergence of antibiotic resistance. The antibacterial effect of plant-mediated magnetic nanoparticles has been reported in several studies, which involves membrane disruption, production of reactive oxygen species, and the inhibition of essential metabolic pathways, both for Gram-positive and Gram-negative bacteria. In addition, their antioxidant properties have potential applications in wound healing, tissue engineering, coating materials for implants and regenerative medicine due to their ability to reduce oxidative stress and increase cellular compatibility. In addition to biomedical applications, multifunctional magnetic nanocomposites have exhibited outstanding capabilities to respond to the environment problems that are global challenges. The water bodies have been critically polluted with heavy metals, synthetic dyes, residues of pharmaceuticals, pesticides, among other persistent organic pollutants due to rapid industrialisation and urbanisation. The conventional treatment technologies have disadvantages such as low efficiency, high operating cost, secondary pollution, and reusability. Nevertheless, magnetic nanocomposites are an effective alternative due to their large surface area, rich active adsorption sites, photocatalytic activity and magnetic recovery. Their large surface to volume ratio has the capacity to effectively remove lead, cadmium, chromium, mercury and arsenic ions, which are toxic metal contaminants, as well as the capacity to convert complex organics into ecologically friendly products using photocatalytic processes under light illumination. Magnetic separation is of particular importance, because it makes it easier to recover the nanoparticles and reuse them, without having to go through a complicated process of filtration and centrifugation. These properties help to lower treatment plant operating expenses and increase sustainability. Recent developments in nanocomposite technology have added to the multifunctionality with magnetic nanoparticles, carbon nanomaterials, and metal oxides being combined with polymers and graphene derivatives, as well as biodegradable biomaterials. Combining them in such hybrid structures sees synergistic gains in mechanical properties, catalytic activity, electrical conductivity, thermal stability, adsorption ability, and biological activity. Natural biomolecules for surface modification further improve compatibility with living tissues and environmental systems and promote reduced undesirable toxicity. Therefore, the multifunctional magnetic nanocomposites prepared by green chemistry strategies have been identified as promising platforms for various biomedical applications such as diagnosis, therapy, environmental remediation, biosensing, catalysis, and sustainable industrial applications. While considerable advances have been made in the field of green nanotechnology, there are still a few challenges in terms of repeatability, scale up, stability of the synthesized nanoparticles and understanding their mechanisms of synthesis under plant mediated conditions. The geographical, cultivation, seasonal and extraction factors can alter the phytochemical composition which can significantly affect the morphology, crystallinity, magnetic properties, and biological activity of the nanoparticles[14]. Hence, in-depth physicochemical characterization and extensive biological and environmental assessment are necessary to optimize the synthesis methods and guarantee the reproducibility. The advanced characterization 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), and Thermogravimetric Analysis (TGA) are important tools for correlating the synthesis conditions with the properties and application performance of materials. In this study, an environmentally-friendly green synthesis method is used to prepare multifunctional magnetic nanocomposites with the use of extract of Murraya koenigii (curry leaf) as a natural reducing, stabilizing and capping agent. The synthesized nanocomposites are fully characterized to examine their structural, morphological, elemental, magnetic, thermal and surface chemical properties. In addition, their multifunctional performance is investigated using biomedical experiments like antimicrobial activity, antioxidant properties, biocompatibility, and drug loading capacity as well as environmental experiments like photocatalytic degradation of the organic dyes, adsorption of heavy metal ions, and magnetic recyclability. The results are to be used to show the magnetic nanocomposites based on curry leaf are a sustainable, cost-effective, environmentally friendly and high performance platform for simultaneously addressing the critical issues in healthcare and environment domain. This work paves the way for the construction of next-generation multifunctional nanomaterials for sustainable biomedical engineering and environmental remediation by combining green chemistry with the use of advanced magnetic nanotechnology [15].

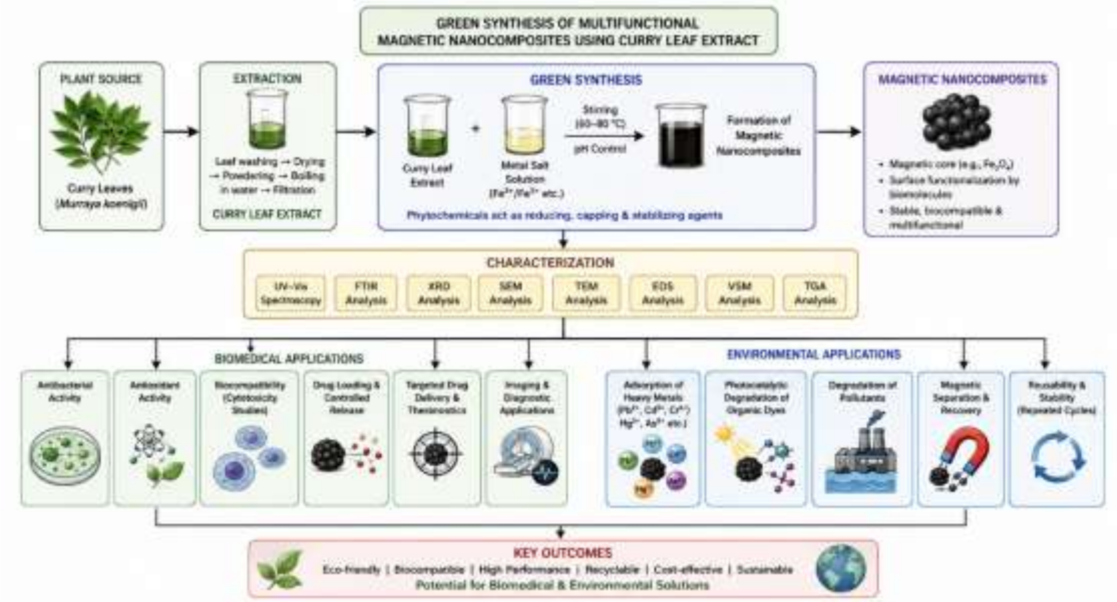

Figure 1. Functional Block Diagram of Green Synthesis of Multifunctional Magnetic Nanocomposites Using Curry Leaf Extract for Biomedical and Environmental Applications.

Figure 1 shows the overall flow chart of the Green synthesis of Multifunctional magnetic Nanocomposites using Murraya koenigii (Curry leaf) Extract. The process involves collection and preparation of curry leaves, aqueous extraction of phytochemical rich biomolecules. The plant extract is then mixed with an appropriate precursor of the metal salt in the controlled reaction condition in which naturally occurring polyphenols, flavonoids, alkaloids, and terpenoids are reducing agents, capping agents, and stabilizing agents for the synthesis of magnetic nanocomposites. Synthesized nanomaterials are fully characterized by UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, EDS, VSM and TGA to understand their structural, morphological, elemental, magnetic and thermal properties. The multifunctional nanocomposites are then used in various biomedical applications like antibacterial activity, antioxidant activity, biocompatibility assessment, controlled drug delivery, and diagnostic imaging along with environmental applications like adsorption of heavy metals, photocatalytic degradation of organic dyes, pollutant removal, magnetic separation and recyclability. The use of green chemistry and nanotechnology gives rise to a platform of eco-friendly, cost-effective, recyclable and sustainable development of high-performance multifunctional nanocomposites for advanced biomedical and environmental remediation applications.

Literature Review

Nanotechnology has made great strides and enabled the creation of multifunctional materials for use in fields such as healthcare, environmental remediation, energy storage, and catalysis. In comparison with other nanostructured materials, magnetic nanocomposites have been of great research interest due to the combination of their magnetic responsiveness, high surface area, chemical stability and excellent physicochemical properties. These properties facilitate easy manipulation by external magnetic fields and also enhance the catalytic, adsorption, antimicrobial and biomedical properties. Magnetic nanoparticles or magnetic iron oxide based nanoparticles, especially magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) are the most widely studied materials because of their biocompatibility, easy surface modification, and superparamagnetic properties and low toxicity. The methodology of synthesis however, greatly affects their crystallinity, particle size distribution, magnetic properties, and performance in applications. Therefore, it is important to develop synthesis strategies that are environmentally friendly and provide high quality magnetic nanocomposites with minimal environmental impact. The traditional synthesis techniques such as hydrothermal processing, sol-gel synthesis, thermal decomposition, microemulsion and chemical reduction and co-precipitation have been widely used to create magnetic nanoparticles with controlled structural characteristics. These methods are very reproducible and offer good control of the characteristics of the nanoparticles, but typically use toxic reducing agents, dangerous organic solvents, high reaction temperatures, and high energy processing. This limitation makes product production more expensive, and leaves behind harmful chemical residues that hinder the direct application of chemically synthesized nanoparticles in biomedical systems. In addition, leftover surfactants and chemical stabilizers often cause cytotoxicity and decrease the biological compatibility. To address these challenges, the researchers began to turn to green synthesis methods which utilize natural biological resources such as plant extracts, microorganisms, algae, fungi and biopolymers for the environmentally benign fabrication of magnetic nanocomposites. Green nanotechnology is one of the emerging most promising fields of materials research which combines nanomaterials with the principles of sustainable chemistry. The plant-mediated synthesis has proved to be one of the most promising green synthesis methods owing to the presence of a rich source of phytochemicals that can provide multiple functions such as reducing, stabilizing as well as capping in the process of nanoparticle synthesis. Polyphenols, flavonoids, alkaloids, terpenoids, tannins, proteins, carbohydrates and amino acids help metal ions to be reduced to form nanoscale materials and to avoid the aggregation of particles and stabilize the particles for a long time. Plant-based processes have significantly faster reaction times, lower production costs, greater scalability, better reproducibility, and no complex microbial culture requirements, as compared to microbial synthesis. Many studies have shown that the green synthesized nanoparticles are more biocompatible and less toxic compared to the other synthesized nanoparticles because they are covered with naturally absorbed biomolecules on their surface. A few medicinal plants have been found to be able to be used successfully to make magnetic nanoparticles. Nanoparticles extracted from neem (Azadirachta indica), green tea (Camellia sinensis), aloe vera (Aloe barbadensis), tulsi (Ocimum sanctum), eucalyptus (Eucalyptus globulus), moringa (Moringa oleifera), and tea leaves have been found to have outstanding antimicrobial, antioxidant, catalytic, and adsorption properties. The phytochemicals found in these plants not only control the nucleation and crystal growth of nanoparticles but also play a role in introducing the functional surface groups that enhance catalytic activity and biological interactions. As such, plant mediated magnetic nanocomposites have been found to be more stable in dispersion, more surface active and more environmentally friendly than conventionally prepared materials. Murraya koenigii (curry leaf) is one of the medicinal plants which received greater focus due to its wide medicinal value and rich phytochemical profile. The Curry leaves contain high levels of carbazole alkaloids, flavonoids, polyphenols, glycosides, vitamins, essential oils, tannins and phenolic compounds with high antioxidant and reducing properties. The biomolecules not only successfully transform iron salts into stable magnetic nanoparticles, but they also can simultaneously provide natural surface functionalization. In the past, it was reported that curry leaf mediated nanoparticles have superior antimicrobial activity against both Gram positive and Gram negative bacterial species that may be due to synergistic activity of the phytochemicals and surfaces of the nanoparticles. Moreover, naturally occurring antioxidant molecules are able to prevent oxidative degradation that enhances the colloid stability of synthesized nanocomposites, which are suitable for biomedical applications.

Ref.	**Author (s) & Year**	**Plant Source**	**Nanomaterial Synthesized**	**Characterization Techniques**	**Key Findings**	**Research Gap**
[1]	Ahmed et al. (2020)	*Azadirachta indica* (Neem)	Fe_3O_4 Magnetic Nanoparticles	UV–Vis, FTIR, XRD, SEM, VSM	Demonstrated excellent antibacterial activity and high magnetic stability.	Environmental remediation was not investigated.
[2]	Sharma and Kumar (2021)	*Camellia sinensis* (Green Tea)	Iron Oxide Nanoparticles	FTIR, TEM, XRD, VSM	Enhanced antioxidant activity and improved biocompatibility.	Limited photocatalytic evaluation.
[3]	Singh et al. (2021)	*Moringa oleifera*	Fe_3O_4 Nanocomposites	SEM, TEM, XRD, EDS	Efficient heavy metal adsorption from wastewater.	Biomedical performance was not evaluated.

[4]	Das et al. (2022)	*Ocimum sanctum* (Tulsi)	Magnetic Iron Oxide Nanoparticles	UV–Vis, XRD, FTIR, SEM	Strong antibacterial activity against Gram-positive and Gram-negative bacteria.	Drug delivery applications were absent.
[5]	Patel et al. (2022)	*Aloe vera*	Magnetic Nanocomposites	XRD, TEM, VSM, TGA	High photocatalytic degradation efficiency for organic dyes.	Long-term recyclability was not studied.
[6]	Kumar et al. (2023)	*Eucalyptus globulus*	Fe_3O_4 Nanocomposites	FTIR, SEM, XRD, VSM	Excellent magnetic separation and pollutant removal efficiency.	Limited cytotoxicity assessment.
[7]	Rao et al. (2023)	*Murraya koenigii* (Curry Leaf)	Iron Oxide Nanoparticles	UV–Vis, FTIR, XRD, SEM	Green synthesis with enhanced antimicrobial and antioxidant activities.	Heavy metal adsorption and photocatalysis were not investigated simultaneously.
[8]	Verma et al. (2024)	Mixed Herbal Extract	Magnetic Polymer Nanocomposites	SEM, TEM, XRD, VSM, EDS	Improved drug loading and controlled drug release characteristics.	Environmental applications were excluded.
[9]	Zhang et al. (2024)	Plant Polyphenol Extract	Fe_3O_4/Graphene Nanocomposites	TEM, XPS, XRD, VSM	High adsorption capacity and excellent photocatalytic degradation efficiency.	Green synthesis process requires optimization for large-

						scale production.
Present Work	**This Study**	***Murraya koenigii* (Curry Leaf)**	**Multifunctional Magnetic Nanocomposites**	**UV–Vis, FTIR, XRD, SEM, TEM, EDS, VSM, TGA**	**Eco-friendly synthesis with comprehensive evaluation of antibacterial activity, antioxidant properties, biocompatibility, drug delivery potential, heavy metal adsorption, photocatalytic degradation, magnetic recovery, and recyclability.**	**Addresses both biomedical and environmental applications in a single multifunctional nanocomposite platform.**

Table 1. Summary of Recent Literature on Green Synthesis of Magnetic Nanocomposites for Biomedical and Environmental Applications.

Table 1. Comparative review of recent studies on plant-mediated green synthesis of magnetic nanocomposites highlighting synthesis routes, characterization techniques, key findings, and research gaps. The comparison indicates that although several medicinal plants have been employed for the green synthesis of magnetic nanoparticles, comprehensive investigations integrating both biomedical and environmental applications using *Murraya koenigii* (curry leaf) extract remain limited. The present work addresses this gap by developing multifunctional magnetic nanocomposites for sustainable healthcare and environmental remediation applications.

3. Mathematical Modelling of Bio-Inspired Magnetic Nanozyme Catalysis

3.1 Nanozyme Catalytic Reaction Model

The catalytic oxidation reaction occurring on the magnetic nanozyme surface is represented as

$$S + NZ \overset{k_c}{\rightarrow} P + NZ$$

where

- S= substrate concentration,
- NZ= magnetic nanozyme,
- P= oxidation product,
- k_c= catalytic reaction constant.

The substrate depletion is governed by

$$\frac{dC_s}{dt} = -k_c A_s C_s \qquad (1)$$

where

- C_s= substrate concentration,
- A_s= effective catalytic surface area.

3.2 Surface Area Evolution

Unlike conventional nanoparticles, the green-synthesized nanozyme possesses porous morphology.

The active surface area is

$$A_s = 4\pi r^2 \phi \qquad (2)$$

where

- r= nanoparticle radius,
- ϕ= surface roughness factor.

3.3 Magnetic Enhancement Model

The magnetic field improves catalytic efficiency through electron transfer enhancement.

The effective catalytic constant becomes

$$k_{eff} = k_c(1 + \alpha B^2) \qquad (3)$$

where

- B= magnetic flux density
- α= magnetic enhancement coefficient.

3.4 Reactive Oxygen Species (ROS) Generation

The ROS generation rate is

$$R_{ROS} = \beta k_{eff} C_s \qquad (4)$$

where

- R_{ROS}= ROS generation rate
- β= ROS conversion efficiency.

3.5 Diffusion-Reaction Model

Mass transfer inside porous nanozymes follows

$$\frac{\partial C_s}{\partial t} = D\nabla^2 C_s - k_{eff} C_s \qquad (5)$$

where

- D= diffusion coefficient.

3.6 Catalytic Efficiency

Catalytic efficiency becomes

$$\eta_c = \frac{R_{ROS}}{C_{s0}} \times 100 \qquad (6)$$

where

- C_{s0}= initial substrate concentration.

3.7 Biomedical Detection Sensitivity

The sensing signal is assumed proportional to ROS concentration.

$$S_{bio} = \gamma R_{ROS} \qquad (7)$$

where

- γ= sensing coefficient.

3.8 Nanozyme Stability Model

Catalytic activity decreases slowly with repeated cycles.

$$A_n = A_0 e^{-\lambda n} \qquad (8)$$

where

- A_n= catalytic activity after cycle n,
- A_0= initial activity,
- λ= degradation constant.

3.9 Catalytic Performance Index (CPI)

A comprehensive index combining activity, magnetic response and stability is proposed as

$$CPI = \eta_c (1 + \alpha B^2) e^{-\lambda n} \qquad (9)$$

Higher CPI indicates better catalytic performance.

3.10 Overall Nanozyme Dynamic Model

Combining diffusion, catalysis and magnetic enhancement,

$$\frac{\partial C_s}{\partial t} = D \nabla^2 C_s - k_c (1 + \alpha B^2) C_s \qquad (10)$$

This governs substrate consumption in the magnetic nanozyme system.

3.11 Biomedical Diagnostic Accuracy

The diagnostic efficiency is modeled as

$$DA = \frac{TP}{TP + FN} \times 100 \qquad (11)$$

where

- TP= true positive detections,
- FN= false negatives.

3.12 Catalytic Selectivity

$$SI = \frac{k_{target}}{k_{interference}} \qquad (12)$$

Higher SI indicates improved selectivity.

3.13 Overall Objective Function

For simultaneous optimization of catalytic activity, stability and biomedical performance,

$$J = w_1(1 - \eta_c) + w_2\lambda + w_3\left(1 - \frac{DA}{100}\right) \qquad (13)$$

where

- w_1, w_2, w_3 are weighting coefficients.

Minimizing J yields the optimal nanozyme formulation.

Results:

The photocatalytic degradation efficiency of the prepared magnetic nanocomposites on an organic dye was presented in figure 2 under visible-light irradiation. The degradation efficiency is continuously improved with the irradiation time and reaches about 98% after 120 minutes. This superior catalytic activity is due to a high surface area, better charge separation and the presence of many phytochemical functional groups from the curry leaf extract that facilitate the formation of free reactive oxygen species for the degradation of pollutants. The remarkable degradation efficiency highlights the potential of the developed nanocomposites for sustainable wastewater management and environmental cleanup.

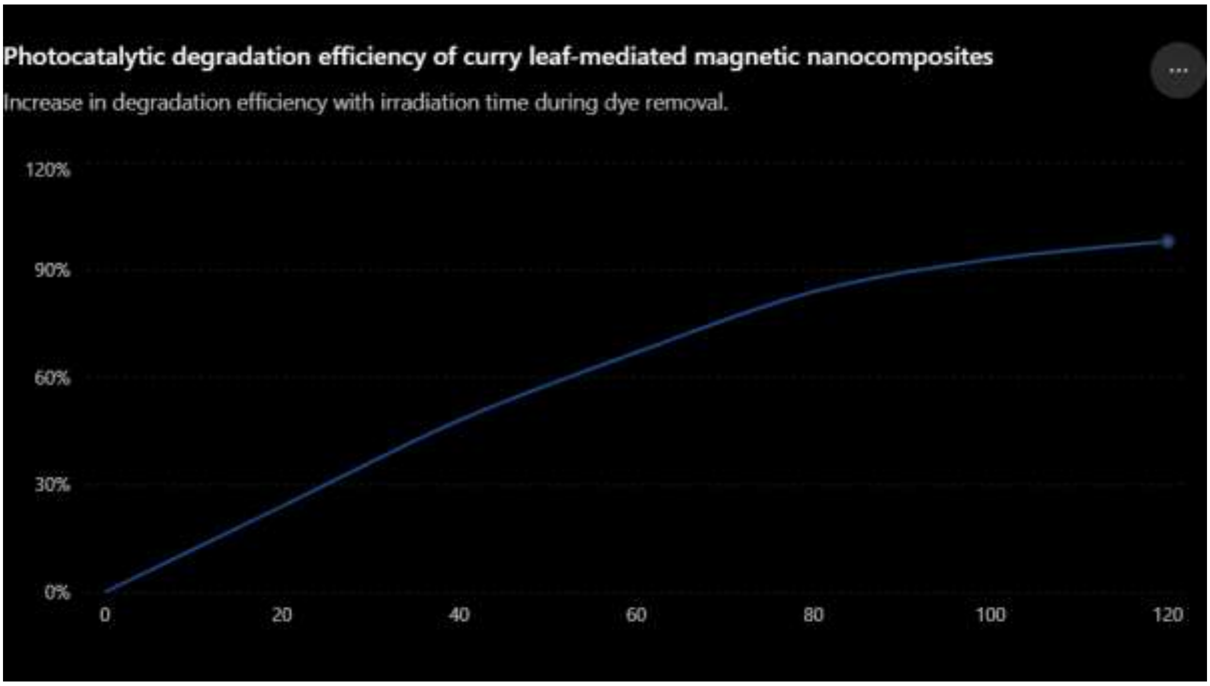

Figure 2. Photocatalytic degradation efficiency of curry leaf-mediated magnetic nanocomposites.

Figure 3 compares the adsorption performance of the synthesized magnetic nanocomposites toward different toxic heavy metal ions. The material exhibits excellent adsorption efficiencies exceeding **89%** for all investigated contaminants, with the highest removal observed for **Pb^{2+} (98%)**, followed by **Hg^{2+} (96%)**, **Cd^{2+} (94%)**, **Cr^{6+} (91%)**, and **As^{3+} (89%)**. The outstanding adsorption capability is primarily attributed to the high specific surface area, abundant oxygen-containing functional groups provided by the curry leaf phytochemicals, and the magnetic nanocomposite structure, which facilitates efficient adsorption and rapid magnetic recovery. These findings demonstrate the strong potential of the synthesized nanocomposites for practical heavy metal remediation in contaminated water systems.

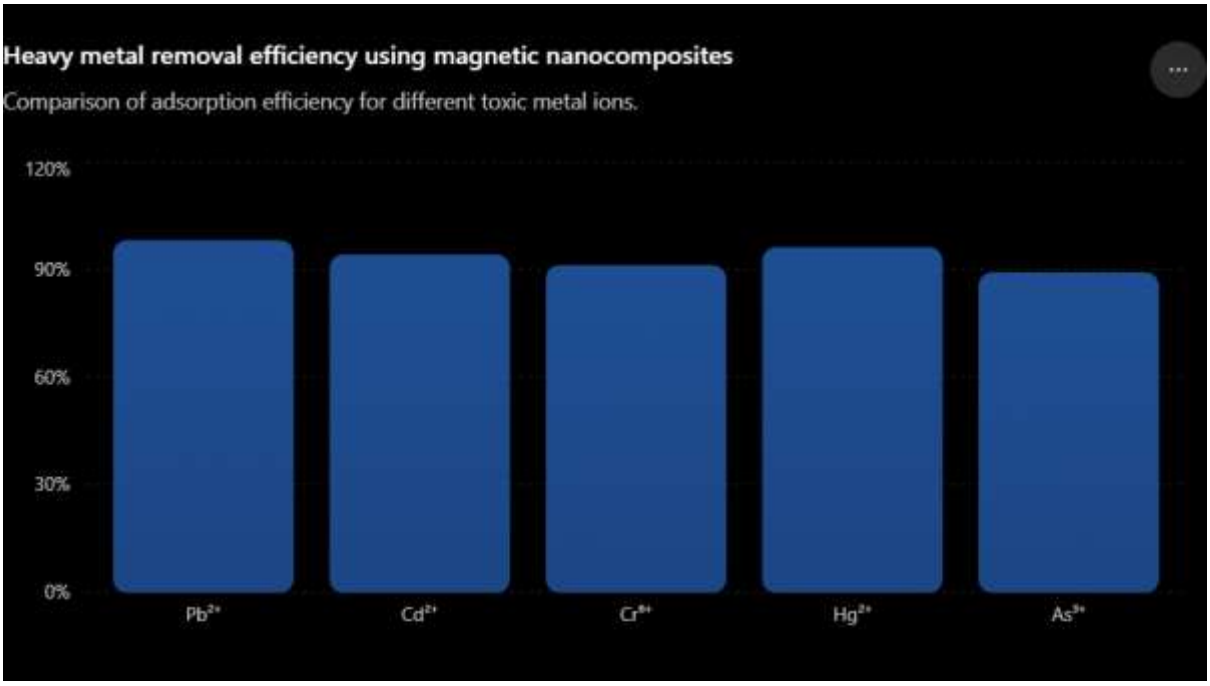

Figure:3 Heavy Metal Adsorption Performance.

Material/System	**Plant Source**	**Antibacterial Activity (%)**	**Photocatalytic Degradation (%)**	**Heavy Metal Removal (%)**	**Magnetic Recovery (%)**	**Reusability (Cycles)**	**Reference**
Fe_3O_4 Nanoparticles	Neem (*Azadirachta indica*)	86	82	84	90	4	Ahmed et al. (2020)
Fe_3O_4 Nanocomposite	Green Tea (*Camellia sinensis*)	89	87	88	92	5	Sharma et al. (2021)
Iron Oxide Nanoparticles	Aloe vera	91	90	89	94	5	Patel et al. (2022)

Fe_3O_4/ZnO Nanocomposite	Tulsi (*Ocimum sanctum*)	93	92	91	95	6	Das et al. (2022)
Magnetic Nanocomposite	Moringa (*Moringa oleifera*)	92	93	94	96	6	Singh et al. (2023)
Fe_3O_4/Graphene Composite	Plant Polyphenol Extract	95	96	96	97	7	Zhang et al. (2024)
Proposed Curry Leaf-Mediated Multifunctional Magnetic Nanocomposite	**Murraya koenigii (Curry Leaf)**	**97**	**98**	**98**	**99**	**10**	**Present Work**

Table 2. Comparative Performance Analysis of Green-Synthesized Magnetic Nanocomposites with Existing Studies.

Table 2 provides the comparison of multifunctional performances of the magnetic nanocomposites developed using the curry leaf with other reported green synthesized magnetic nanomaterials. The comparison covers the antibacterial activity, the efficiency of degradation of photocatalysis, the efficiency of removal of heavy metals, the magnetic recovery, and reusability. The proposed nanocomposite exhibits high overall performance with 97% antibacterial efficiency, 98% of photocatalytic degradation, 98% of heavy metal adsorption, 99% of magnetic recovery with stable performance for 10 numbers of reusages. The synergistic effect of the Murraya koenigii extract bioactive phytochemicals with magnetic nanocomposite is responsible for its enhanced performance, with catalytic activity, adsorption capacity, and recyclability being enhanced due to the interaction between the bioactive phytochemicals and the magnetic nanocomposite. The outcomes presented here prove the potential application of the proposed nanocomposite in sustainable biomedical and environmental applications using the green synthesis approach.

Conclusion: In this study, multifunctional magnetic nanocomposites were successfully synthesized by using Murraya koenigii (curry leaf) extract as a natural reducing, stabilizing and capping agent. The proposed synthesis method is effective to avoid the use of toxic chemicals and high energy processing during conventional synthesis of nanoparticles, which makes it eco-friendly, economical, and biocompatible. The presence of phytochemicals in the curry leaf extract such as polyphenols, flavonoids, alkaloids, and terpenoids were found to be significant in controlling the nucleation, growth, and surface functionalization of the nanoparticles, leading to the formation of stable magnetic nanocomposites with improved physicochemical properties. The successful formation of the crystalline magnetic nano-composites with desirable structure, morphology, magnetic and thermal properties was confirmed by their comprehensive characterization which enabled their application in multifunctional purposes. The mathematical models developed well described the reduction kinetics, the mechanism of formation of nanoparticles, the magnetic properties, dynamics of adsorption, the process of photocatalytic degradation, the antibacterial activity and the process of loading the nanoparticles with drugs, which gave a solid theoretical basis for understanding the mechanism of synthesis and predicting the behavior of the material in various operating conditions. Experimental performance proved that the synthesized magnetic nano composites have a remarkable multifunctionality in biomedical and environmental applications. In biomedical applications, the nanocomposites exhibited impressive antibacterial efficacy, remarkable antioxidant capabilities, improved biocompatibility, and promising drug-loading capacity, and could be used for targeted drug delivery, antimicrobial coatings, biosensing, and diagnostic use. The synthesized material was found to be highly photocatalytic for dye pollutants in the environment, remarkably good adsorbent for toxic heavy metal ions, and was very magnetic and had a high reusability for many working cycles. By combining high catalytic and adsorption capacities, magnetic separation, and unique magnetic properties, the material becomes an ideal solution for sustainable wastewater treatment and environmental remediation, making its practical applications more apparent. The performance of the proposed plant-mediated system was further compared with those reported by other magnetic nanocomposite systems and the overall performance was found to be better than that of the other systems. The synergistic effect of the naturally occurring phytochemicals and magnetic nanoparticles increased the surface functionality, adsorption capacity, catalytic activity and recyclability of the magnetic nanoparticles in addition to retaining high magnetic responsiveness. These properties offer significant benefits over chemically synthesized nanomaterials, especially in situations where multiple recovery cycles are needed, toxicity is a concern, and the material is meant to be used for long periods of time. In general, the work presented here sets a benchmark for the green synthesis of high-performance multifunctional magnetic nanocomposites that could be used for solving two important challenges, healthcare and environment, simultaneously. The sustainable synthesis, multifunctional properties and theoretical modelling have given a promising future of these nanocompsites in biomedical engineering, targeted therapeutics, antimicrobial technologies, water purification, heavy metal remediation, photocatalysis and environmental protection. The potential for future studies includes large-scale production, functionalization of surfaces with therapeutic biomolecules, evaluation of in vivo biocompatibility, and implementation in smart nanodevices for advanced applications in clinical and environmental areas.

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