

Phytochemical-Assisted Synthesis of Manganese-Magnesium Binary Oxide Nanoparticles

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Abstract

This study reports the green synthesis and characterization of manganese-magnesium binary oxide nanoparticles (Mn–Mg NPs) using aqueous extracts of *Ficus exasperata* leaves, a phytochemically rich plant native to West Africa. The biosynthesis involved reacting manganese and magnesium acetate precursors with the plant extract under controlled pH and thermal conditions, followed by centrifugation, rinsing, drying, and calcination. Comprehensive characterization via FTIR, XRD, BET, SEM-EDS, and DLS confirmed successful nanoparticle formation. FTIR revealed phytochemical-mediated functional groups, while XRD indicated crystalline structures. BET analysis showed a high surface area of 281.992 m²/g, suggesting strong adsorption potential. SEM and EDS confirmed nanoscale morphology and elemental composition, and DLS analysis revealed uniform particle size (92.65 nm) with low polydispersity (PDI = 0.208). The results demonstrate that *Ficus exasperata* extract is an effective green route for synthesizing Mn–Mg NPs with desirable properties for environmental applications.

1. Introduction

Nanomaterials are a class of materials with at least one dimension in the nanometer range (1–100 nm), and their unique physicochemical properties have enabled transformative applications across disciplines such as medicine, electronics, catalysis, and environmental remediation. Among these, nanoparticles (NPs) defined as particles possessing at least one nanoscale dimension have garnered particular attention due to their high surface area-to-volume ratio, quantum confinement effects, tunable morphology, and enhanced reactivity [1]. The functional efficiency and application potential of nanoparticles are inherently tied to critical parameters such as particle size, shape, crystallinity, and chemical composition, all of which are governed by the synthesis approach employed.

Generally, nanoparticle synthesis is categorized into top-down and bottom-up approaches. Conventional bottom-up methods include hydrothermal synthesis, sol-gel processing, co-precipitation, chemical reduction, seeding, laser pyrolysis and electrodeposition techniques. While effective, many of these methods rely on hazardous chemicals, generate toxic by-products, and require energy-intensive conditions, raising concerns regarding environmental safety and sustainability.

In response to these limitations, green synthesis or biosynthesis of nanoparticles has emerged as a viable and eco-conscious alternative. This approach leverages biological resources such as plants, bacteria, fungi, and algae as reducing and stabilizing agents, thereby eliminating or minimizing the use of toxic solvents and reagents [2]. Among these, plant-mediated synthesis stands out due to its simplicity, scalability, cost-effectiveness, and the presence of diverse phytochemicals that facilitate controlled nanoparticle formation [3]. Plant-derived metabolites such as polyphenols, flavonoids, terpenoids, alkaloids, phenolic acids, and proteins can effectively reduce metal ions and stabilize the resulting nanoparticles through capping interactions [4,5]. Consequently, numerous plant parts—leaves, stems, flowers, fruits, and roots—have been explored for nanoparticle synthesis [6], offering a high degree of control over nanoparticle characteristics.

Compared to microbial biosynthesis, plant-mediated approaches offer faster reaction kinetics, broader nanoparticle size and morphology control, and easier scalability [6]. Green synthesis is aligned with the principles of green chemistry, which emphasize the use of environmentally benign solvents and renewable feedstocks, reduction of waste, and the adoption of inherently safer chemical processes [7]. In this context, *Ficus exasperata* (Vahl) commonly referred to as the "sandpaper tree" and widely distributed across West African vegetation zones—offers immense potential for phytomediated nanoparticle synthesis. It belongs to the Moraceae family, comprising over 45 species found in Nigeria alone, spanning diverse ecological zones from savannas to rainforests and riparian habitats [8]. Phytochemical analyses of *F. exasperata* have revealed the presence of saponins, tannins, phenolic compounds, carbonyl groups, and alcohols, which are instrumental in nanoparticle biosynthesis as reducing and capping agents[9]. Its abundance, renewable nature, and rich phytochemical profile make *F. exasperata* an excellent candidate for green synthesis applications.

Building on this foundation, the present study explores the phytochemical-assisted synthesis of manganese-magnesium binary oxide nanoparticles (Mn–Mg NPs) using aqueous extracts of *F. exasperata* leaves. The aim is to develop an environmentally benign synthesis route for Mn–Mg NPs with potential applications in adsorption and catalysis, supported by detailed characterization using FTIR, XRD, BET, SEM-EDS, and DLS techniques. This study contributes to advancing green nanotechnology by valorizing indigenous plant resources for sustainable nanomaterial production.

2. Materials and Methods

2.1 Reagents

All reagents used in this study were of analytical grade and were utilized without any further purification. Deionized distilled water was employed throughout all experimental procedures.

2.2 Plant Sample Collection and Aqueous Extraction

Fresh leaves of *Ficus exasperata* were collected from the Ugbowo Campus of the University of Benin, Benin City, Nigeria. Botanical authentication was performed by Professor Akinnibosun of the Department of Plant Biology and Biotechnology, University of Benin, and the specimen was deposited in the departmental herbarium under voucher number UBH-F319.

The collected leaves were thoroughly washed with distilled water to remove adhering contaminants, air-dried at ambient room temperature to preserve bioactive constituents, and then pulverized using a mechanical grinder to obtain a uniform powder.

The aqueous extraction was carried out following the method described by [10]. with slight modifications. Briefly, 50 g of the powdered leaf material was suspended in 500 mL of distilled water and heated at 60°C for 2 hours under continuous magnetic stirring to ensure complete dispersion and

extraction of phytoconstituents. After cooling to room temperature, the mixture was filtered using Whatman No. 1 filter paper. The clear filtrate was collected and stored at 4°C for subsequent use in nanoparticle synthesis.

2.3 Green Synthesis of Manganese–Magnesium Binary Oxide Nanoparticles

The green synthesis of manganese–magnesium (Mn–Mg) binary oxide nanoparticles was performed via a plant-mediated co-precipitation method, adapted from [11], with modifications. A 0.1 M solution of manganese (II) acetate tetrahydrate $[(\text{CH}_3\text{COO})_2 \text{Mn} \cdot 4\text{H}_2\text{O}]$ was prepared by dissolving 2.45 g of the salt in distilled water and diluting to 100 mL in a volumetric flask. Similarly, a 0.1 M solution of magnesium acetate tetrahydrate $[(\text{CH}_3\text{COO})_2 \text{Mg} \cdot 4\text{H}_2\text{O}]$ was prepared by dissolving 2.15 g of the salt and making up to volume in a separate 100 mL flask.

For the nanoparticle synthesis, 100 mL of each metal precursor solution (Mn^{2+} and Mg^{2+}) was mixed with 20 mL of the previously prepared *F. exasperata* leaf extract in a 500 mL borosilicate beaker. The mixture was heated at 60°C for 1 hour under constant stirring. Subsequently, 1 M NaOH was added dropwise to adjust the pH to the alkaline range of 10–11, promoting the nucleation and growth of oxide nanoparticles. The reaction was maintained at 60°C for an additional 2 hours to complete the synthesis.

After the reaction, the mixture was allowed to cool to room temperature and then centrifuged at 10,000 rpm for 10 minutes. The precipitate was washed with distilled water and re-centrifuged three times to remove unreacted components and excess plant metabolites. The resulting product was dried in a hot-air oven at 102°C for 1 hour. The dried material was then calcined in a muffle furnace at 500°C for 3 hours to obtain crystalline Mn–Mg binary oxide nanoparticles. The final product was preserved in a desiccator and subjected to physicochemical and structural characterization.

2.4 Characterization of the Binary Oxide Nanoparticles

The synthesized manganese–magnesium binary oxide nanoparticles were subjected to comprehensive physicochemical characterization using various analytical techniques. Fourier Transform Infrared Spectroscopy (FTIR) was utilized to identify the surface functional groups and assess the chemical bonding interactions between phytochemicals and the nanoparticle surfaces. Spectra were recorded in the range of 4000–400 cm^{-1} . X-ray Diffraction (XRD) analysis was employed to determine the crystalline structure, phase purity, and average crystallite size of the nanoparticles using the Scherrer equation. The diffraction patterns were recorded using Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$). Scanning Electron Microscopy (SEM) was used to investigate the surface morphology, particle shape, and agglomeration state of the nanoparticles. Complementary elemental analysis was conducted using Energy Dispersive X-ray Spectroscopy (EDS) attached to the SEM system to determine the qualitative and quantitative elemental composition, confirming the presence and distribution of Mn and Mg within the nanomaterial matrix.

Brunauer–Emmett–Teller (BET) surface area analysis was carried out to evaluate the specific surface area, pore size distribution, and porosity characteristics of the nanoparticles, providing insights into their potential for surface-driven applications.

Dynamic Light Scattering (DLS) analysis will be conducted to determine the hydrodynamic particle size distribution and polydispersity index (PDI), offering information on colloidal stability and particle dynamics in suspension.

3. Results and Discussion

3.1 Characterization of the synthesized nanoparticles

3.1.1 Functional Group Analysis

The Fourier-transform infrared (FTIR) spectrum of manganese-magnesium binary oxide nanoparticles synthesized using *Ficus exasperata* leaf extract provides critical insights into the functional groups involved in nanoparticle stabilization and formation (Fig. 1). The spectrum, spanning from 4000 to 400 cm^{-1} , reveals several significant absorption bands indicative of both organic phytochemicals from the plant extract and metal-oxygen bonds confirming nanoparticle formation.

A broad and intense absorption band observed around 3400 cm^{-1} corresponds to O–H stretching vibrations, typically attributed to hydroxyl groups present in polyphenols, alcohols, and possibly water molecules adsorbed on the nanoparticle surface. This band suggests the presence of hydrogen bonding and supports the role of plant-derived biomolecules as reducing and capping agents [12].

A weaker peak observed near 2920 cm^{-1} is assigned to C–H stretching vibrations, likely from aliphatic –CH₂– or –CH₃– groups, which further confirms the involvement of organic moieties from the leaf extract in the nanoparticle matrix. The absorption band around 1630 cm^{-1} can be attributed to C = O stretching or N–H bending vibrations, typically arising from carbonyl or amine groups in proteins or flavonoids, reinforcing the bio-functionalization of the nanoparticle surfaces [13].

Notably, a distinct band appearing around 1100 cm^{-1} corresponds to C–O–H bending vibrations, supporting the presence of polysaccharides or other oxygenated functional groups that may contribute to nanoparticle dispersion and stabilization [13]. Critically, the fingerprint region below 800 cm^{-1} reveals sharp bands associated with metal–oxygen (M–O) stretching vibrations. Specifically, absorption bands in the region of 500–600 cm^{-1} confirm the formation of Mn–O and Mg–O bonds, affirming the successful synthesis of manganese-magnesium binary oxide nanoparticles. The presence of these peaks signifies the incorporation of both metal ions into the oxide matrix and validates the dual-metal nanoparticle composition [13,14]. The FTIR spectrum demonstrates that phytochemicals from *Ficus exasperata* act as effective reducing and stabilizing agents during nanoparticle synthesis, while characteristic M–O vibrations substantiate the formation of binary metal oxides. The spectrum provides

a comprehensive confirmation of bio-assisted synthesis and surface functionalization, which are essential for nanoparticle stability and potential biological applications.

The X-ray Diffraction (XRD)

The XRD result revealed the phase and crystallinity of the nanoparticles, as shown in Fig. 2. It was observed that the nanoparticles were crystalline. The phase view also shows the major compounds identified as pyrolusite (MnO_2) and periclase (MgO), and the other compounds present are as shown in table 1. The XRD pattern showed peaks at $2\theta = 29^\circ, 38^\circ, 43^\circ, 29^\circ, 57^\circ$, which can be indexed as follows 300, 211, 301, 600, respectively, it is in agreement with XRD standard card JSPDF 44-0141, suggesting tetragonal crystalline of MnO_2 , [15]. The peaks at $2\theta = 37.5^\circ, 44^\circ$, and 62° , can be indexed as follows 111, 200 and 220, respectively, it is in alignment with XRD standard card JSPDF 75-0447, suggesting hexagonal crystalline of MgO [16,17].

The X-ray diffraction (XRD) analysis of the manganese-magnesium binary oxide nanoparticles synthesized using *Ficus exasperata* leaf extract reveals a well-defined crystalline structure characterized by distinct and sharp peaks across the 2θ range of 10° to 70° (Fig. 2). The pattern demonstrates the successful formation of a multiphase nanomaterial with contributions from manganese and magnesium oxide species, as evidenced by the presence of several prominent diffraction maxima.

A major peak centred around $2\theta = 18.0^\circ$ is attributed to the (111) reflection of pyrolusite (MnO_2), a tetragonal manganese dioxide phase known for its catalytic and electrochemical properties. This suggests the predominant incorporation of manganese in its oxidized form during the biosynthesis process, likely facilitated by the oxidative phytochemicals present in *Ficus exasperata* extract. Another intense peak at approximately $2\theta = 28.7^\circ$ can be assigned to the (311) plane of jacobsite (MnFe_2O_4), a spinel-structured manganese ferrite phase. The emergence of this peak may indicate the formation of a mixed-metal oxide matrix, possibly enhanced by trace metal ions present in the reaction environment or introduced via plant-mediated redox interactions.

The peak observed at $2\theta = 36.5^\circ$ corresponds to the (111) reflection of periclase (MgO), a thermodynamically stable cubic magnesium oxide phase [16,17]. This confirms the incorporation of magnesium into the crystalline framework, contributing to the binary oxide structure [15]. Additional weaker peaks appearing at 2θ values of approximately $42.5^\circ, 56.7^\circ$, and 62.1° suggest the formation of minor crystalline domains or mixed-phase oxide structures, which may arise from the synergistic interaction between manganese and magnesium species during the nucleation and growth stages of nanoparticle formation. These secondary reflections support the presence of a heterogeneous, yet highly crystalline, nanocomposite system [16,17].

The sharpness and intensity of the observed peaks imply a high degree of crystallinity and uniformity in particle size distribution. This structural order is indicative of effective plant-mediated synthesis, where bioactive compounds in the *Ficus exasperata* extract function as both reducing and stabilizing agents,

facilitating controlled growth of nanocrystals. Furthermore, the absence of broad amorphous halos suggests that the synthesized material is primarily crystalline, with negligible amorphous content.

The XRD pattern confirms the successful green synthesis of a manganese-magnesium binary oxide nanocomposite featuring characteristic reflections of pyrolusite, periclase, and jacobsite phases. The interplay of these oxide components likely imparts multifunctional properties to the nanomaterial, making it a promising candidate for applications in catalysis, environmental remediation, and biomedicine. The use of *Ficus exasperata* as a sustainable synthesis route further underscores the eco-friendly nature of the process, aligning with current trends in green nanotechnology.

Surface Area Analysis

The BET results provide critical insights into the surface area, porosity, and adsorption properties of the nanoparticles, which are essential for their performances for various applications (Fig. 3). The slope of the BET plot, measured at 9.958, and the intercept of 2.391×10^0 , with a high correlation coefficient ($r = 0.990636$), indicate excellent data reliability and a strong linear relationship between the measured pressure and adsorption. This strong correlation underscores the precision of the BET model in describing the adsorption characteristics of the Mn-Mg binary oxide nanoparticles. The accurate BET model fit validates the calculated surface area and demonstrates that the nanoparticles exhibit a uniform adsorption behaviour, which is crucial for their consistent performance.

The most striking feature of the BET analysis is the surface area of $281.992 \text{ m}^2/\text{g}$. This exceptionally high surface area is a critical factor in enhancing the adsorption capacity of the nanoparticles. The surface area also influences the distribution and accessibility of active sites on the nanoparticles. Moreover, the green synthesis approach of the Mn-Mg binary oxide nanoparticles may confer additional advantages, such as the incorporation of functional groups or defects that further enhance adsorption and catalytic activity.

The result of the BET energy parameter, $E = 0.807 \text{ kJ/mol}$, as shown in Fig. 4 below highlights the moderate interaction energy between the nanoparticles and adsorbed species. This energy level indicates that the adsorption process likely follows a physical adsorption mechanism. Physical adsorption is characterized by the formation of van der Waals bonds, which allow for reversible adsorption-desorption cycles. The parameter $n = 1.000$, suggests that the adsorption process is highly uniform and fits a Langmuir-type adsorption isotherm. This result indicates monolayer coverage of adsorbates on the nanoparticle surface. The micropore volume of 0.254 cc/g is a critical parameter that underscores the material's high porosity.

The structural features of the Mn-Mg binary oxide nanoparticles, derived from the BET analysis, are complemented by the environmentally friendly synthesis approach. The green synthesis method not only ensures minimal environmental impact during nanoparticle production but may also contribute to the material's functionality.

The results highlight a substantial surface area of 354.166 m²/g, which is particularly significant in the context of environmental remediation and catalytic applications (Fig. 5). Such a high specific surface area is indicative of a well-developed porous structure, providing an extensive interface for interaction with surrounding molecules. In adsorption processes, the surface area is a critical determinant of performance, as it governs the number of active sites available for contaminant capture. The greater the surface area, the more surface-active sites are exposed, thereby enhancing the adsorption capacity and overall efficiency of the material in sequestering pollutants such as heavy metals, dyes, and organic contaminants from aqueous and gaseous media.

Complementing this high surface area is the pore volume, measured at 0.173 cc/g, which further reinforces the material's aptitude for adsorption-based applications. Pore volume refers to the total void space within the nanoparticles and is directly related to the capacity of the material to accommodate adsorbate molecules. A relatively large pore volume, as observed in this study, suggests that the nanoparticles can host a substantial quantity of contaminants within their internal structure, in addition to those adsorbed on the external surface. This property is especially important in dynamic systems where the adsorbent must accommodate fluctuating contaminant concentrations over time.

Additionally, the average pore diameter ($D_v(d)$) of 2.132 nm classifies the material as mesoporous, as it falls within the 2–50 nm range defined by IUPAC for mesopores. Mesoporous materials are known for their balanced combination of high surface area and optimal pore size, which not only facilitates rapid diffusion and accessibility of target molecules into the interior pores but also minimizes diffusional resistance. This is particularly advantageous for applications involving relatively large molecules or where rapid adsorption kinetics are desired. In the context of catalysis, the mesoporous architecture allows for better dispersion of active sites and improved reactant transport, leading to enhanced catalytic efficiency.

Collectively, the BET (Brunauer–Emmett–Teller) surface area, pore volume, and pore diameter data provide strong evidence of the Mn-Mg binary oxide nanoparticles' structural suitability for use in environmental cleanup technologies, such as wastewater treatment, air purification, and even soil remediation. The synergistic effect of high surface area and mesoporosity underpins the material's potential for high-performance adsorption, making it a promising candidate for sustainable and efficient environmental interventions.

Microscopic Analysis

The SEM micrographs presented in Fig. 6 reveal critical insights into the morphological characteristics of Mn-Mg Binary Oxide Nanoparticles synthesized via *Ficus exasperata* leaf extract. These micrographs, captured at magnifications corresponding to 30 μm (a) and 100 μm (b), elucidate the surface topology, particle distribution, and agglomeration tendencies of the synthesized nanomaterial.

In Fig. 6a (30 μm scale), the microstructure exhibits a heterogeneous distribution of nanoparticles with a dense clustering of spherical to irregularly shaped granules. These particles appear to be aggregated

into larger secondary structures, likely as a result of van der Waals forces and partial sintering during the drying or calcination process. The surface appears relatively rough, with numerous protrusions and intergranular voids that contribute to an increased surface area. This morphology is beneficial for catalytic and adsorption applications, as the high density of exposed surfaces and interparticle channels can enhance mass transfer and reactive site availability.

At the finer magnification, one can also observe that the particles are generally nanoscale in nature, consistent with the presence of primary nanoparticles forming larger agglomerates. Such agglomeration is typical of biologically synthesized metal oxides, particularly when plant extracts act as both reducing and stabilizing agents. The phytochemicals present in *Ficus exasperata*—such as polyphenols, flavonoids, and alkaloids—play a crucial role in directing nucleation and growth processes, leading to the observed granular morphology.

Figure 6b (100 μm scale) offers a broader perspective of the material's morphology, emphasizing the overall texture and bulk structure. The field shows a relatively compact and coarse surface with micron-sized agglomerates loosely packed over a porous background. This texture suggests a material that is not only nanostructured but also hierarchically organized, combining micro- and nanoscale features. The presence of larger, irregularly shaped granules interspersed with finer particles points to a poly-dispersed system, possibly indicating incomplete control over growth kinetics during synthesis. However, this diversity in particle size can be advantageous in certain applications, such as in heterogeneous catalysis and adsorption, where a broad pore size distribution may facilitate accessibility to various reactants or contaminants.

Both images confirm the successful formation of metal oxide nanoparticles and reflect the efficiency of the green synthesis approach in producing materials with favorable morphological attributes. Notably, the biosynthesis route using *Ficus exasperata* extract avoids the use of toxic chemicals and provides a sustainable pathway for nanomaterial fabrication. The resulting surface features—roughness, porosity, and aggregated nanostructures—enhance the functional properties of the Mn-Mg binary oxide, rendering it suitable for applications in environmental remediation, catalysis, antimicrobial formulations, and energy storage. The SEM analysis underscores the effective biomediated synthesis of Mn-Mg binary oxide nanoparticles, characterized by a porous, agglomerated, and rough microstructure with hierarchical particle organization. These morphological features directly support the material's high surface area and mesoporosity observed in BET analysis, thereby corroborating its potential utility in various advanced functional applications.

Elemental Analysis

Table 1 and Fig. 7 collectively present the elemental composition of Mn-Mg binary oxide nanoparticles synthesized via a green approach using *Ficus exasperata* leaf extract, as determined by Energy Dispersive X-ray Spectroscopy (EDS). The most prominent elements identified in the EDS results are manganese (Mn) and magnesium (Mg), which are present in significant quantities. Manganese, with an atomic concentration of 41.89% and a weight concentration of 61.80%, forms the dominant component

of the nanoparticles. Manganese is well known for its catalytic properties, which makes it highly valuable for applications such as adsorption and degradation of organic contaminants. Magnesium, with an atomic concentration of 48.88% and a weight concentration of 31.90%. The synergy between Mn and Mg in the binary oxide structure contributes to the overall effectiveness of the material in various applications. Other elements detected in trace amounts include Na, Ca, Al, Si, P, S, Cl, and several transition metals, including Fe, K, Ti, and Cr. Na, present with an atomic concentration of 6.55% and a weight concentration of 4.05%, may originate from the green synthesis process and could influence the material's surface properties, Ca and Al, with atomic concentrations of 0.69% and 0.96%, respectively, are also present in small amounts. Si, P, S, and Cl are present in trace amounts, which may be residual elements from the green synthesis route or impurities in the starting materials. Notably, the absence of significant amounts of Fe, K, Ti, and Cr suggests that these elements do not substantially contribute to the composition of the Mn-Mg binary oxide nanoparticles. The lack of these elements is beneficial for ensuring that the nanoparticles remain non-toxic and environmentally friendly, aligning with the sustainability goals of the green synthesis method.

Table 1: Elemental composition of Mn-Mg binary oxide nanoparticles synthesized via a green approach, as determined by Energy Dispersive X-ray Spectroscopy (EDS)

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
25	Mn	Manganese	41.89	61.80
12	Mg	Magnesium	48.88	31.90
11	Na	Sodium	6.55	4.05
20	Ca	Calcium	0.69	0.75
13	Al	Aluminium	0.96	0.69
14	Si	Silicon	0.68	0.51
15	P	Phosphorus	0.19	0.16
16	S	Sulfur	0.10	0.09
17	Cl	Chlorine	0.05	0.05
26	Fe	Iron	0.00	0.00
19	K	Potassium	0.00	0.00
22	Ti	Titanium	0.00	0.00
24	Cr	Chromium	0.00	0.00

Size Analysis

The dynamic light scattering (DLS) analysis of the synthesized Mn-Mg binary oxide nanoparticles offers critical insights into their physicochemical characteristics, particularly their size distribution and degree of dispersion (Fig. 8). The average hydrodynamic diameter was recorded at 92.65 nm, confirming that the particles fall well within the nanometer scale, which is essential for their enhanced reactivity and surface-related functionalities. Nanoparticles within this size range possess a high surface-to-volume ratio, which significantly boosts the availability of surface-active sites, thereby improving their interaction with surrounding media—especially important for applications such as catalysis, adsorption, and biomedical delivery systems.

Additionally, the polydispersity index (PDI) was determined to be 0.208, a value that reflects a relatively narrow and uniform size distribution. In DLS analysis, the PDI ranges from 0 (perfectly monodisperse) to 1 (highly polydisperse). A PDI of 0.208 indicates that the nanoparticles are well-dispersed with minimal size variation, which is highly desirable. Uniformity in particle size contributes to predictable and consistent behavior in both chemical and biological systems. It minimizes issues such as aggregation and ensures more efficient packing, transport, and surface interaction in practical applications. Overall, the DLS results affirm the structural integrity and suitability of the Mn-Mg binary oxide nanoparticles for advanced functional uses.

Conclusion

This study successfully demonstrates the eco-friendly synthesis of manganese-magnesium binary oxide nanoparticles (Mn–Mg NPs) using *Ficus exasperata* leaf extract, harnessing the plant's phytochemical richness to facilitate a sustainable and non-toxic approach to nanomaterial fabrication. The green synthesis method, involving metal acetate precursors and plant-derived reducing agents under controlled thermal and pH conditions, yielded well-defined nanoparticles after subsequent purification and calcination steps. Comprehensive physicochemical characterization confirmed the formation and quality of the Mn–Mg NPs. FTIR analysis identified functional groups from plant metabolites responsible for reduction and stabilization, while XRD patterns confirmed the crystalline nature of the nanoparticles. BET surface analysis revealed a notably high specific surface area (281.992 m²/g), underscoring the material's strong adsorption potential. SEM micrographs and EDS spectra validated the nanoscale morphology and elemental composition of the synthesized product, and DLS analysis revealed a narrow size distribution with an average particle size of 92.65 nm and a low PDI of 0.208, indicating good uniformity and dispersion. Collectively, these findings affirm the potential of *Ficus exasperata* as an efficient, green synthetic agent for fabricating Mn–Mg NPs with tailored properties suitable for a wide range of environmental applications, particularly in pollutant remediation and catalysis. This work contributes to the growing body of research promoting sustainable nanotechnology and highlights the value of leveraging indigenous plant resources for advanced material development.

Declarations

Ethical Approval and Consent to Participate

Not applicable. This study did not involve any human participants, animals, or biological materials requiring ethical approval or informed consent.

Consent for Publication

Not applicable.

Availability of Data and Materials

All data generated or analyzed during this study are included in this published article. Additional data, if required, are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

Human and Animal Rights

This article does not contain any studies with human participants or animals performed by any of the authors.

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Figures

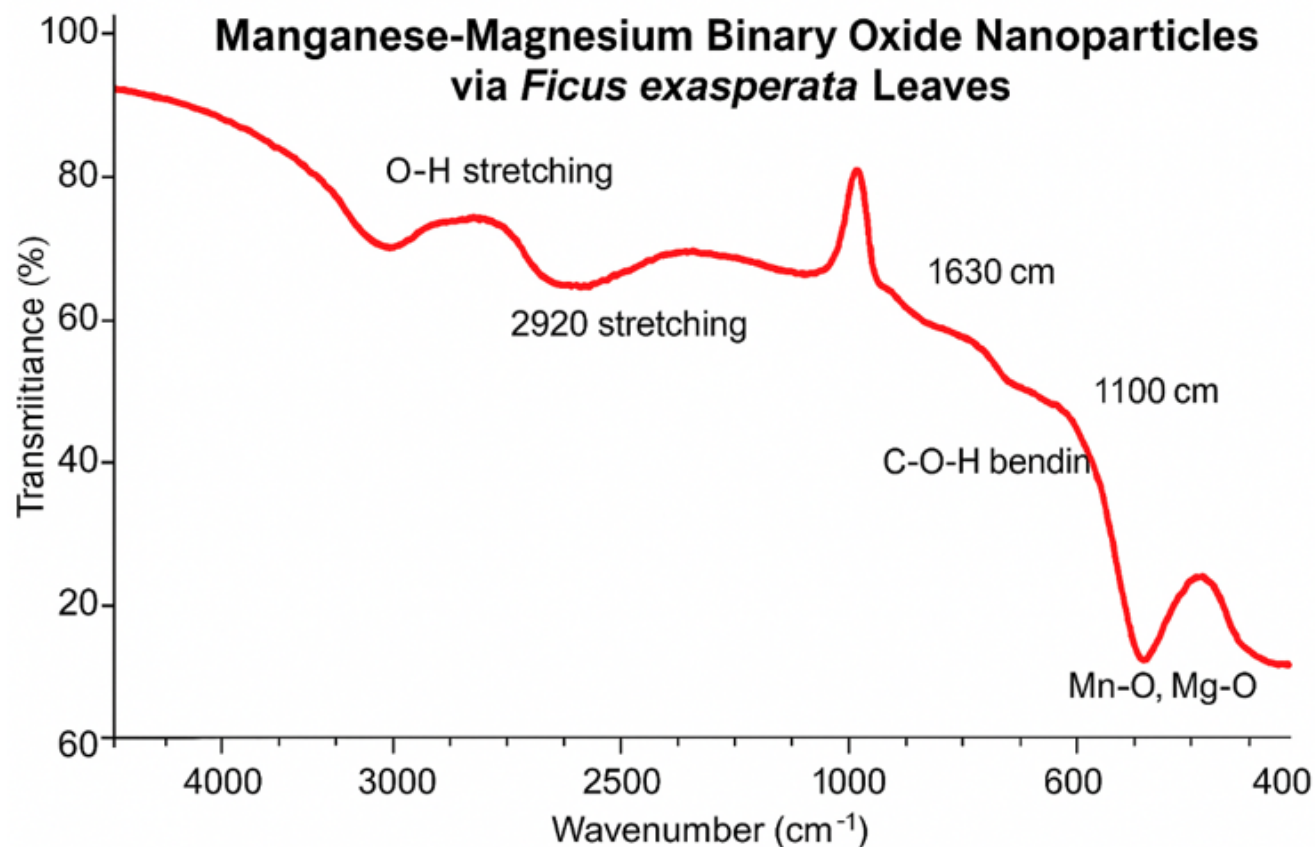


Figure 1

FTIR result of green synthesized manganese-magnesium binary oxide nanoparticles

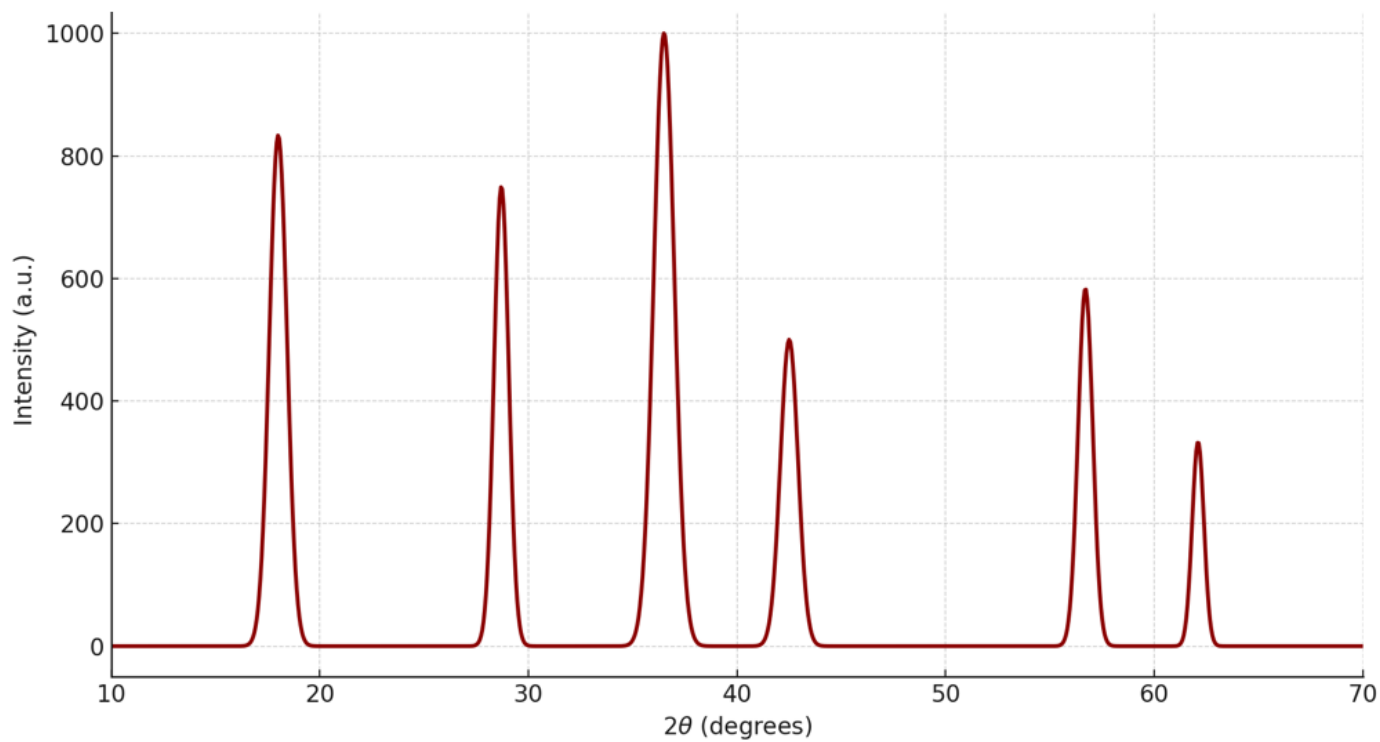


Figure 2

Result showing phase view pattern of XRD analysis of Mn-Mg binary oxide

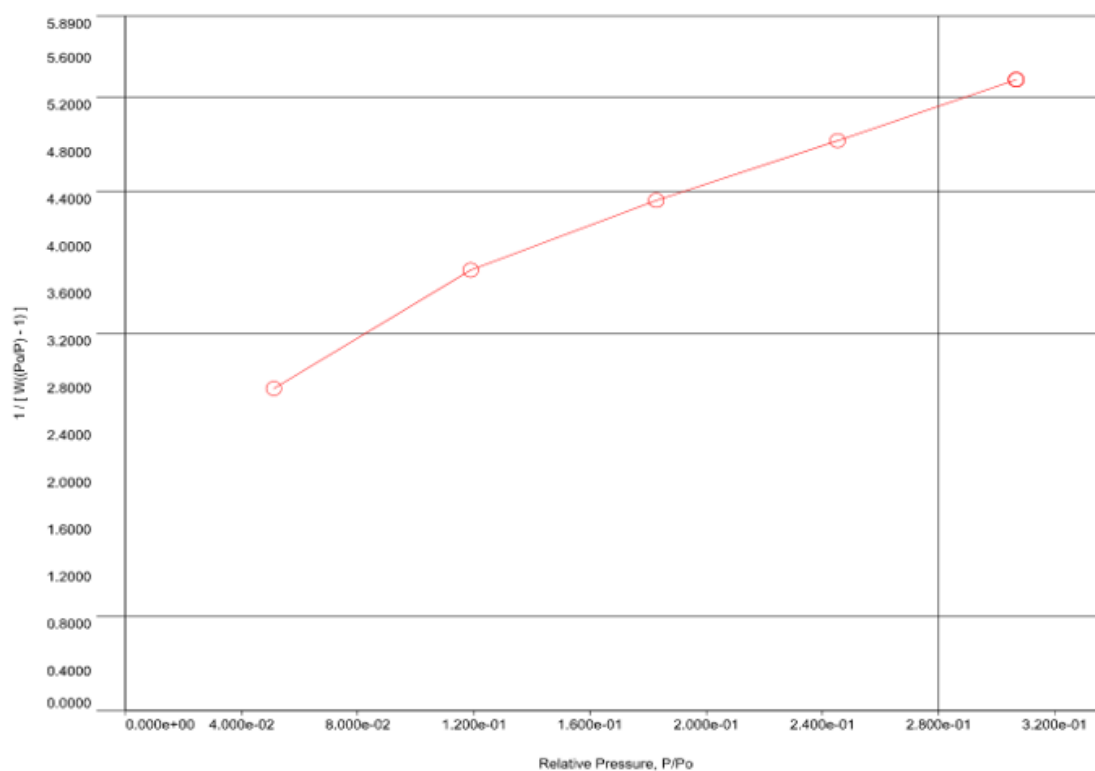


Analysis		Report	
Operator:	Abdulrahman Abdulkareem	Operator:	Abdulrahman Abdulkareem
Sample ID:	With Extract	Filename:	With Extract.qps
Sample Desc:		Comment:	
Sample weight:	0.15 g	Sample Volume:	1 cc
Outgas Time:	3.0 hrs	Outgas Temp:	250.0 C
Analysis gas:	Nitrogen	Bath Temp:	273.0 K
Press. Tolerance:	0.100/0.100 (ads/des)	Equil time:	60/60 sec (ads/des)
Analysis Time:	121.3 min	End of run:	2024/12/06 12:31:07
Cell ID:	1	Equil timeout:	240/240 sec (ads/des)
		Instrument:	Nova Station A

Multi-Point BET Plot

Adsorbate		Data Reduction Parameters		
Nitrogen		Temperature	77.350K	
Molec. Wt.: 28.013		Cross Section:	16.200 Å²	
		Liquid Density:	0.808 g/cc	

A



BET summary	
Slope =	9.958
Intercept =	2.391e+00
Correlation coefficient, r =	0.990636
C constant =	5.165
Surface Area =	281.992 m²/g

Figure 3

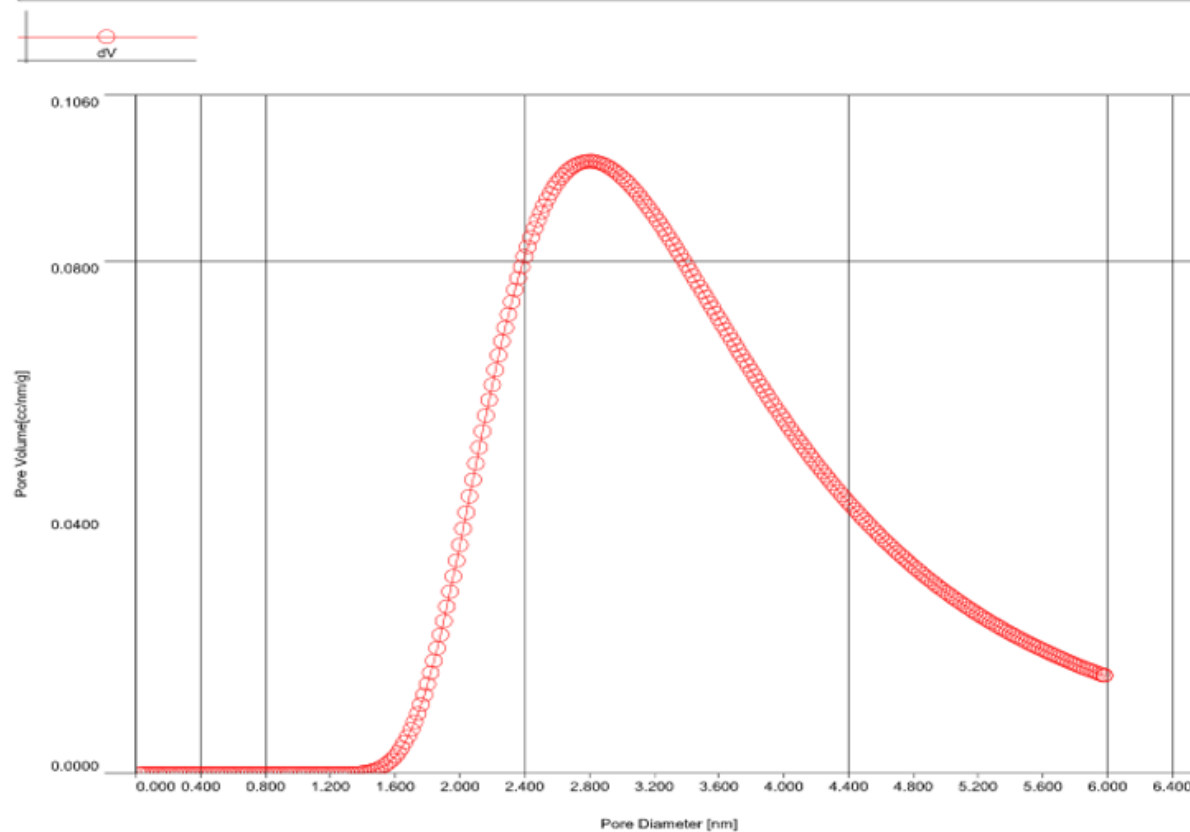
(BET) analysis of Mn-Mg binary oxide nanoparticles synthesized via a green approach.



Analysis		Report	
Operator:	Abdulrahman Abdulkareem	Operator:	Abdulrahman Abdulkareem
Sample ID:	With Extract	Filename:	With Extract.qps
Sample Desc:		Comment:	
Sample weight:	0.15 g	Sample Volume:	1 cc
Outgas Time:	3.0 hrs	Outgas Temp:	250.0 C
Analysis gas:	Nitrogen	Bath Temp:	273.0 K
Press. Tolerance:	0.100/0.100 (ads/des)	Equil time:	60/60 sec (ads/des)
Analysis Time:	121.3 min	End of run:	2024/12/06 12:31:07
Cell ID:	1	Equil timeout:	240/240 sec (ads/des)
		Instrument:	Nova Station A

DA Plot

DA Method		Data Reduction Parameters		
Adsorbate	Incr. E:	500.000	Incr. n:	0.100
	Nitrogen		Temperature	77.350K
	Molec. Wt.:	28.013	Cross Section:	16.200 Å ²
		Interact. Const. (K):		2.960nm ³ x kJ / mol
		Liquid Density:		0.808 g/cc



DA method summary
 Best E = 0.807 kJ/mol
 Best n = 1.000
 DA Micropore Volume = 0.254 cc/g
 Pore Diameter (mode) = 2.800e+00 nm

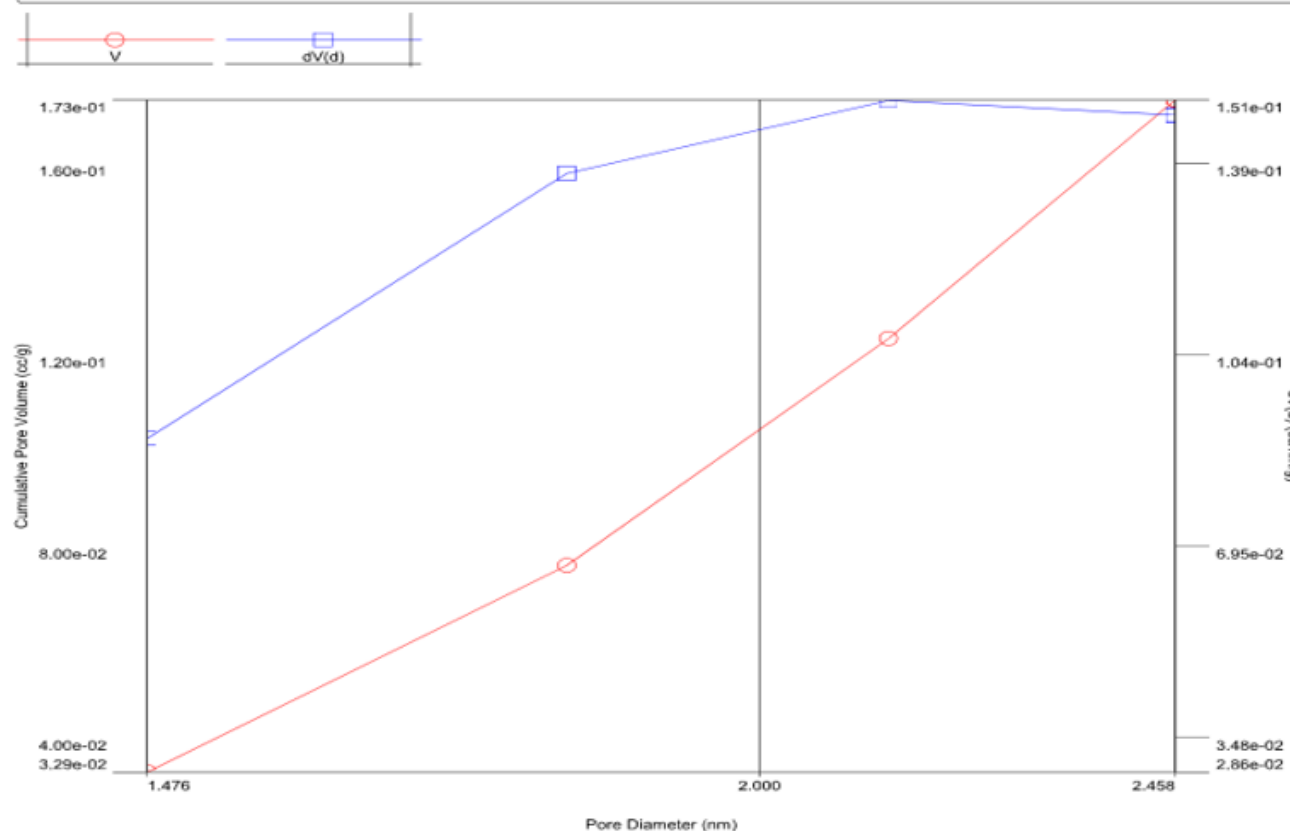
Figure 4

BET analysis of Mn-Mg binary oxide nanoparticles showing adsorption energy ($E=0.807$ kJ/mo), uniform adsorption behavior ($n=1.000$), micropore volume (0.254 cc/g), and mesopore diameter (2.800 nm)

Analysis		Report	
Operator:	Abdulrahman Abdulkareem	Operator:	Abdulrahman Abdulkareem
Sample ID:	With Extract	Filename:	With Extract.qps
Sample Desc:		Comment:	
Sample weight:	0.15 g	Sample Volume:	1 cc
Outgas Time:	3.0 hrs	Outgas Temp:	250.0 C
Analysis gas:	Nitrogen	Bath Temp:	273.0 K
Press. Tolerance:	0.100/0.100 (ads/des)	Equil time:	60/60 sec (ads/des)
Analysis Time:	121.3 min	End of run:	2024/12/06 12:31:07
Cell ID:	1	Equil timeout:	240/240 sec (ads/des)
		Instrument:	Nova Station A

BJH method Adsorption dV(d)

Data Reduction Parameters			
t-Method	Calc. method: de Boer	Temperature	77.350K
BJH/DH method	Moving pt. avg.: off	Cross Section:	16.200 Å ²
Adsorbate	Molec. Wt.: 28.013	Liquid Density:	0.808 g/cc



BJH adsorption summary

Surface Area =	354.166 m ² /g
Pore Volume =	0.173 cc/g
Pore Diameter Dv(d) =	2.132 nm

Figure 5

BJH (Barrett–Joyner–Halenda) adsorption analysis of Mn-Mg binary oxide nanoparticles synthesized via a green approach, revealing a high surface area of 354.166 m²/g, pore volume of 0.173 cc/g, and mesoporous diameter of 2.132 nm.

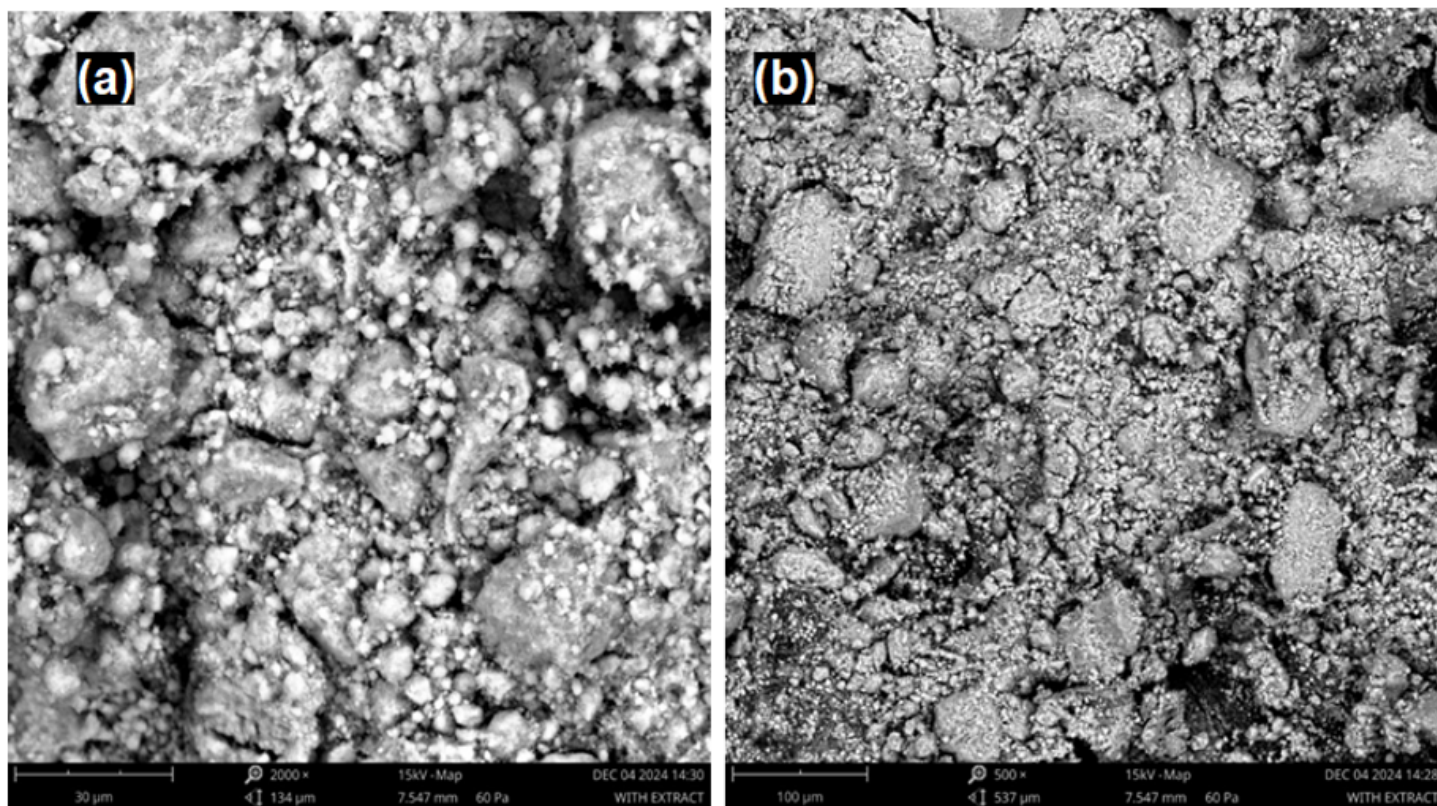


Figure 6

SEM micrograph of Mn-Mg Binary Oxide Nanoparticles via *Ficus exasperata* Leaves (a) 30 µm and (b) 100 µm

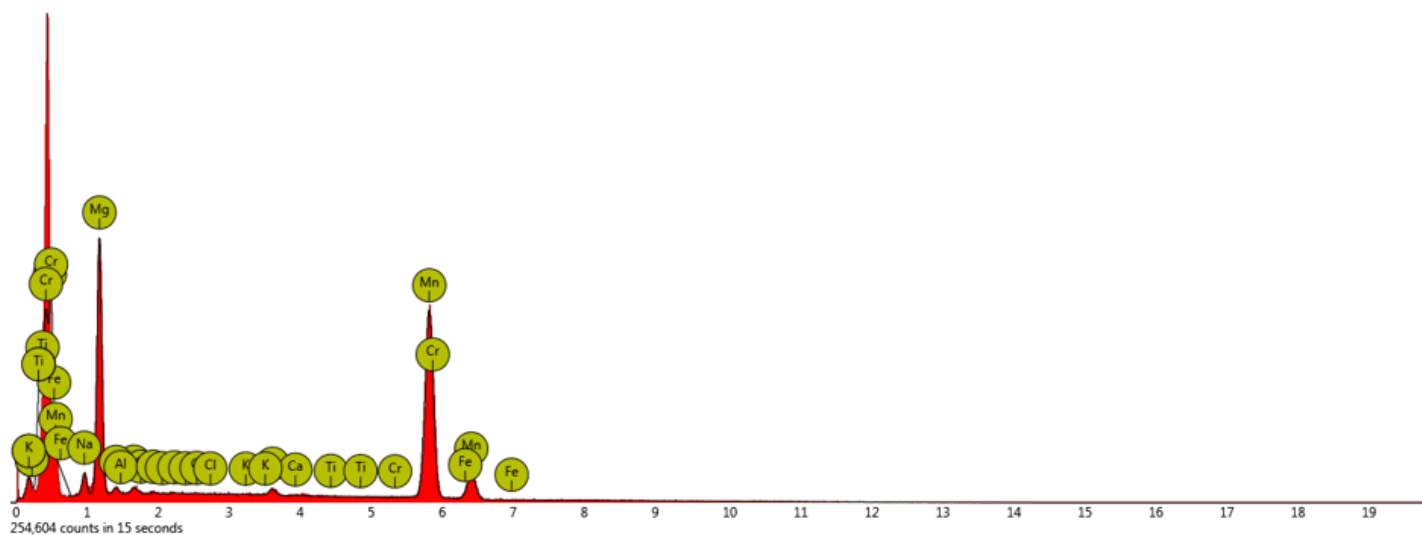


Figure 7

Elemental composition of Mn-Mg binary oxide nanoparticles synthesized via a green approach, as determined by Energy Dispersive X-ray Spectroscopy (EDS)

Results

	Size (d.n...	% Number:	St Dev (d.n...
Z-Average (d.nm): 92.65	Peak 1: 0.7142	0.1	0.1607
Pdl: 0.208	Peak 2: 3.133	0.1	0.4112
Intercept: 0.757	Peak 3: 8.670	27.8	2.220
Result quality Good			

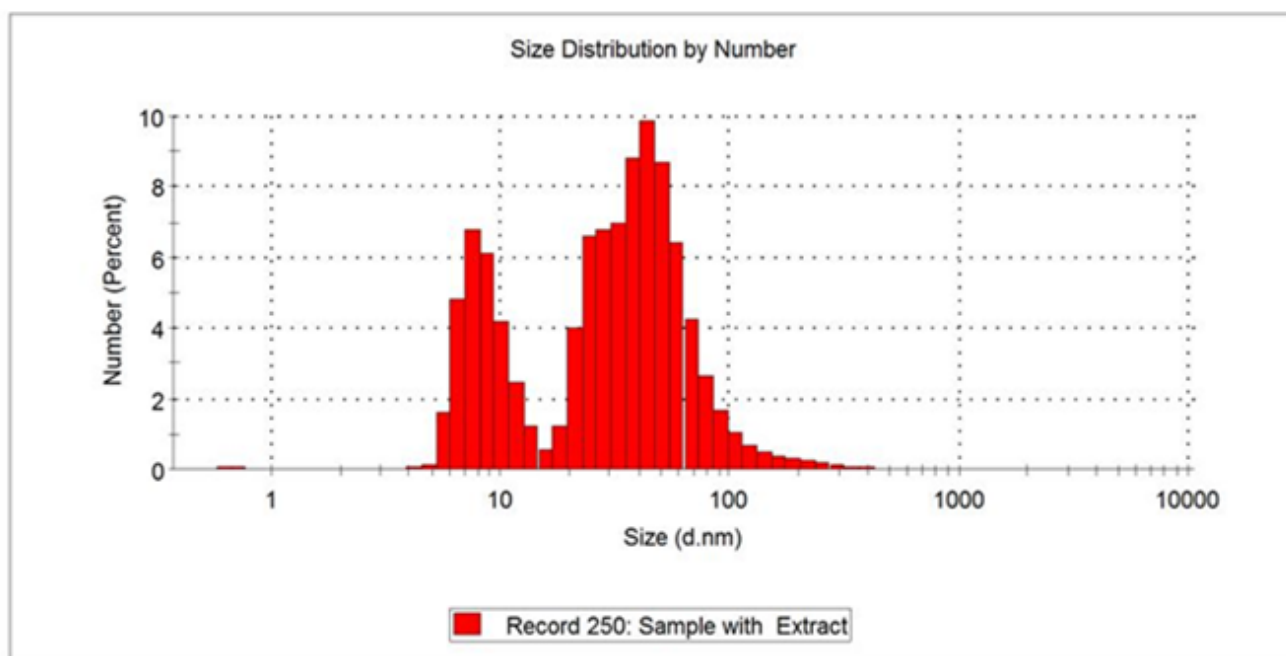


Figure 8

Dynamic light scattering (DLS) analysis of Mn-Mg binary oxide nanoparticles

Supplementary Files

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- [GraphicalAbstract.png](#)