Green Synthesis of CuO/MgO Nanocomposites Using Mangifera indica Leaf Extract: Characterization and Biological Applications

Shiva Soni
shivasoni21@gmail.com

Poornima University

Vivek Kumar Jain
Poornima University

Preetam Singh
Jaipur National University

Honey Satiya

Research Article

Keywords: Green synthesis, nanocomposites, bimetallic nanoparticles, CuO/MgO, antimicrobial activity

Posted Date: June 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9864090/v1

Additional Declarations: No competing interests reported.

Green Synthesis of CuO/MgO Nanocomposites Using Mangifera indica Leaf Extract: Characterization and Biological Applications

Shiva Soni[1], Vivek Kumar Jain[2], Preetam Singh[3], Honey Satiya[4]

[1,2] Department of Physics, Poornima University, Jaipur, Rajasthan, 303905, India

[3] Department of Physics, Jaipur National University, Jaipur, Rajasthan, 302017, India

[4]Independent Researcher, Jaipur, Rajasthan, 302017, India

Email: [1]shivasoni21@gmail.com ; [2]vivek.jain@poornima.edu.in;

[3]singhpreetamsingh@gmail.com ; [4] satiyahoney@gmail.com

Corresponding Author : Shiva Soni

Abstract:

Bimetallic nanocomposites have emerged as an important impact innovative material in recent times. We propose the green biological synthesis of bimetallic Copper/Magnesium (Cu/Mg) nanocomposites by incorporating an aqueous extract of Mangifera indica leaves, in response to increasing interest. A broad spectrum of analytical strategies, including UV-vis, FTIR, TEM, XRD, XPS, TGA. The UV–vis spectrophotometer (UV-vis) gave the maximum absorbance at 205 and 257 nm range. The Fourier transform infrared spectroscopy (FTIR) analysis identified active elements in the leaf extract that they functioned as surfactant compounds, stabilizers, capped molecules, and reducing agents, Transmission Electron Microscopy (TEM), were used to determine the optical property and surface morphology of the nanoparticles. whereas TEM image revealed that the material particle size was 20-50 nm. X-ray diffraction (XRD) analysis revealed that the sample that was produced was polycrystalline, with an average particle size of around 37.01 nm.The formation of a CuO/MgO heterojunction has been demonstrated by X-ray photoelectron spectroscopy (XPS) results, which were consistent with TEM and XRD observations.The Thermogravimetric Analysis(TGA) and Derivative Thermogravimetry (DTG) curves show the thermal behaviour of the synthesized CuO/MgO NCs.

The bimetallic nanocomposites (Cu/Mg) demonstrated potential antibacterial and anti-fungal potency, with comprehensive analyses which are provided in detail. The agar well diffusion method was implemented to assess the antimicrobial effectiveness of the copper/magnesium nanocomposites. According to the findings, Mangifera indica leaf extract displays potential antimicrobial activity at various concentrations, ensuring the presence of bioactive substances that are beneficial in medical applications.

Keywords: Green synthesis, nanocomposites, bimetallic nanoparticles, CuO/MgO**,** antimicrobial activity

Graphical Abstract:

1. Introduction:

Nanotechnology involves dealing extensively with various synthesis approaches, nanoparticle structural changes, and particle dimension reformulations. Nanoparticles, on the other hand, are actually crystalline materials having a diameter smallest in size than 100 nm and possess an exceptionally high mechanical, electrical,optical, magnetic, and also material-to-volume ratios, and they also possess extremely stable thermal properties **[1].**Nanotechnology has come into existence as an emerging topic in today's material science research. The fabrication of mono and bimetallic nanocomposites in various forms is of paramount importance since these substances offer numerous paths as well beneficial applications, comprising medicinal drug delivery**[2,3],** conventional water treatment**[4]**, agricultural production**[5],** electronic sensors**[6]**, as well as textile materials.**[7]**Metal nanoparticles can be synthesized utilizing various physical and chemical approaches, which include: sol-gel synthesis,, hydrothermal, chemical reduction laser treatment, as well metallic ion sputtering methods **[8, 9]**.

Bimetallic nanoparticles are gaining growing recognition partly because of their unique characteristics which distinguish them apart from other monometallic nanoparticles **[10-13]**. They possess numerous applications. The process of biosynthesis is more cost-effective and substantial in comparison to chemical and physical fabrication of a nanoparticles, leading to an entirely novel era of bio-nanotechnology **[14]**. Nanomaterials have been synthesized using an assortment of conventional methods, encompassing chemical and biological approaches. Chemical strategies involve the synthesis of nanoparticles employing different chemical precursors, almost all of which are exceedingly toxic and regarded as potential hazards, such as adverse environmental effects [**15**].Despite this, these strategies possess an array of negative aspects that include substantial equipment costs, the requirement of skilled employees, and toxicity in the environment. Consequently, the "green" production method, which employs living organisms and green plants, has become recognized to be the best possible approach to fabricating nanoparticles [**16**].

Several plant extracts have previously been utilized in recent times to synthesize copper magnesium nanoparticles.Numerous metallic nanostructures have been developed fabricated, comprising copper, magnesium, zinc, silver, and platinum nanoparticles **[17–23]**. In addition to this these nanoparticles, copper nanoparticles (Cu-NPs) showed unique features which includes residing affordable, less hazardous than before, having an extensive surface area to volume ratio, and having superior heat transfer performance the fact that might be correlated to their physical attributes such as composition, morphological characteristics, and crystalline structure. This methodology additionally serves as simple and economical as well. Cu-NPs that utilize the approach displayed favorable the structural features and biological activity**[24]**.

Magnesium oxide nanoparticles possess numerous uses, including as sunscreen products, cosmetic products, and textile products on account of their UV-blocking functions. MgO nanoparticles possess antibacterial effects and have been used in antibacterial coatings, textile fabrics, and medical appliances with piezoelectric components properties**[25-28]**.They are utilized in sensing devices, resonating devices, and actuators, respectively.

Here is the literature review, describing that the CuO nanoparticles produced by Gebrie et al. in 2025 using Plumbago zeylanica leaf extract have been identified to be more effective against Gram-negative (E. coli, K. pneumonia and P. aeruginosa) bacteria. The produced CuO NPs' antioxidant activity and IC50 values for DPPH tests were assessed **[29]** .The environmentally friendly synthesis of nanoparticles of magnesium oxide utilizing neem extracts from leaves has been reported by Rabiet et al. **[30]** in 2025. They determined that the antibacterial agents were effective against both Gram-positive (Enterococcus faecalis, Bacillus subtilis, Enterococcus) and Gram-negative (Enterobacter aerogenes, Salmonella Typhimurium,) bacteria.

Cu-Ag nanoparticles made from Carica papaya leaves by Jacob et al. in 2022.It has been found that antibacterial potency against **gram-positive** bacteria S. aureus , B. subtilis and **gram-negative** bacteria Escherichia coli, Pseudomonas aeruginosa, Additionally, research on the in-vitro cytotoxicity activity showed that HeLa cell lines **[31]** are susceptible to cytotoxicity when Cu-Ag bimetallic nanocomposites are tested against conventional doxorubicin.

Green synthesis has received a great deal of attention since it essentially minimizes the quantity of toxic and hazardous chemicals being discharged into the environment using physical and chemical characteristics techniques. Plant-based nanoparticle fabrication is a relatively inexpensive, single-pot process which utilizes phytochemical elements as both a reducing and stabilizing agent in order to generate desired nanoparticles **[32]**.These components are referred to as biogenic nanomaterials **[33]**.Precursors identified primarily in plant leaves, peels of plants, stems, leaves, flowers, fruits, and juices from plants are potentially utilized in order to fabricate plant-produced nanopowders **[34]**, **[35]**.

Considering different properties of CuO and MgO in this investigation , we have reported on a green and environmentally friendly fabrication of CuO/MgO nanocomposites (CM NCs) with the help of **Mangifera indica (M. indica)** green leaves aqueous solution as a reducing and stabilizing agent.

1.1. Description of Mangifera indica:

M. indica is a member of the Anarcardiaceae category of perennial plants with flowers (order Sapindales), which comprises about 80 genera and 870 species of densely wooded vines, shrubs, and evergreen species or deciduous vegetation. The majority of Anacardiaceae species are actually indigenous to tropical and subtropical regions of worldwide distribution, whereas they are frequently identified in India. It is a medicinal plant and has been used as medicine since ancient time in India. India has diverse systems of health which include an which include an Ayurveda, Unani, homeopathic remedies, and naturopathic therapies. These systems, which included widespread, secure, and continuous use of various herbal medications, coexisted with allopathic medicine.**[36]**

Mangifera indica (M.indica) has a variety of pharmacological effects, encompass a range of cancer-preventing, anti-diabetic, anti-oxidative, anti-inflammatory, antibacterial, anti-bacterial, anti-fungal, antiseptic, hepatoprotective, gastroprotective, anti-plasmodial, anti-hyperlipidemic **[37]**,and immune-suppressive properties.**[38] M.indica** contains an array of phytochemicals, such as Mangferin, Catechin, Kaempferol, Gallic Acid, Ellagic acid,Quercetin, Protacatechuic **[39]**etc depicted **in fig 1.**These biological molecules identified in M. indica may act as a non-toxic, ecologically sustainable, and stabilizing element during the fabrication of nanoparticles.

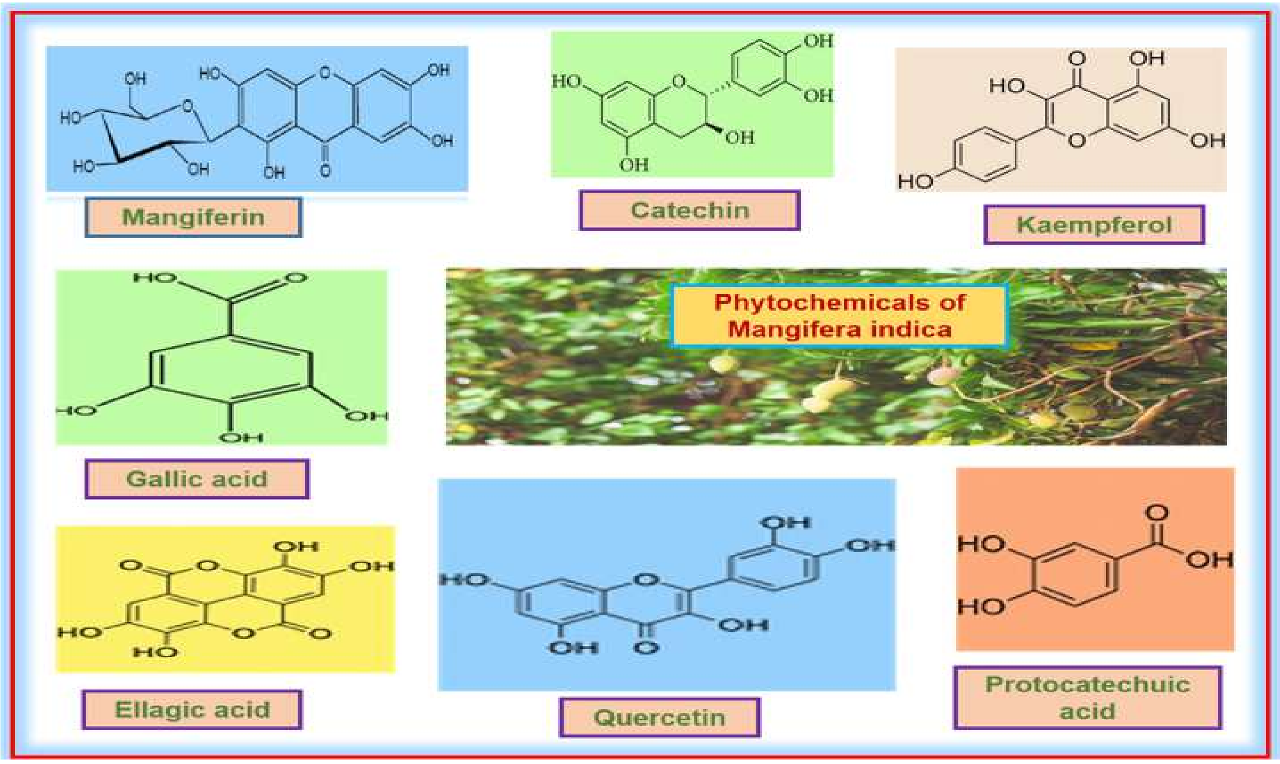

Fig1: Phytochemicals of Mangifera indica (M. indica) Green Leaves

Previously, different species of plants had previously been utilized in the nanoparticle fabrication. Because of their excellent antimicrobial properties, numerous investigators are now exploring the green method of forming bimetallic nanoparticles. Fruits possess higher amounts of phenolic compounds and polymethoxylated flavones than other types of plant.Mangifera indica plant extract, which contributes to the diminution in ions of metals compared to metallic nanoparticles, has been utilized in a green synthetic process to form Cu/Mg nanopcomposites with bimetallic properties during the current study. Besides that, no papers are currently being published on the the green synthesis of Cu/Mg bimetallic nanocomposites prepared from a Mangifera indica leaf extract.

The present investigation examines the role of naturally occurring green extract metabolite compounds as a stabilizing and reducing agent during the production of CuO/MgO NCs.Additionally, several physicochemical methods, such as UV-vis, FTIR, TEM, powder XRD, and XPS, were implemented to confirm the fabrication of green route fabricated CM NCs. Additionally, the effectiveness of antimicrobial of biosynthesized CM NCs has been evaluated towards strains of bacteria which include **Gram-positive:** Staphylococcus aureus, **Gram-negative:** E. coli, and fungal strains such as P. chrysogenum and A. niger has been assessed.

2. Experimental setup, materials and methods

All chemicals utilized throughout the current study are finally analytical grade as well as have been purchased for commercial purposes. Deionized water was being utilized for making the solutions, and the resulting solutions were utilized freshly prepared throughout the duration of the experiment.

2.1. Preparation of Mangifera indica leaves extract:

The green leaves belonging to M. indica had been collected from the campus of Poornima University in India. Afterwards being rinsed via tap water in order to get rid of all tiny fine particles of dirt, the leaves were dried in the shade and subsequently pulverized through the use of an electrical grinder.

20 g of powdered dried plant leaves were dissolved in 200 mL of water that had been double-distilled and thoroughly blended in a 500 mL flask. The resulting extract had been made for 3 hours at 80^0C by utilizing a magnetic heating stirrer. The resulting product suspension had been filtrated via Whatmann's filter paper after being allowed to cool to room temperature. The extracted material **(M. indica)** leaf extract was then preserved in a refrigerator(2°C) for future consumption as shown in **fig 2**.

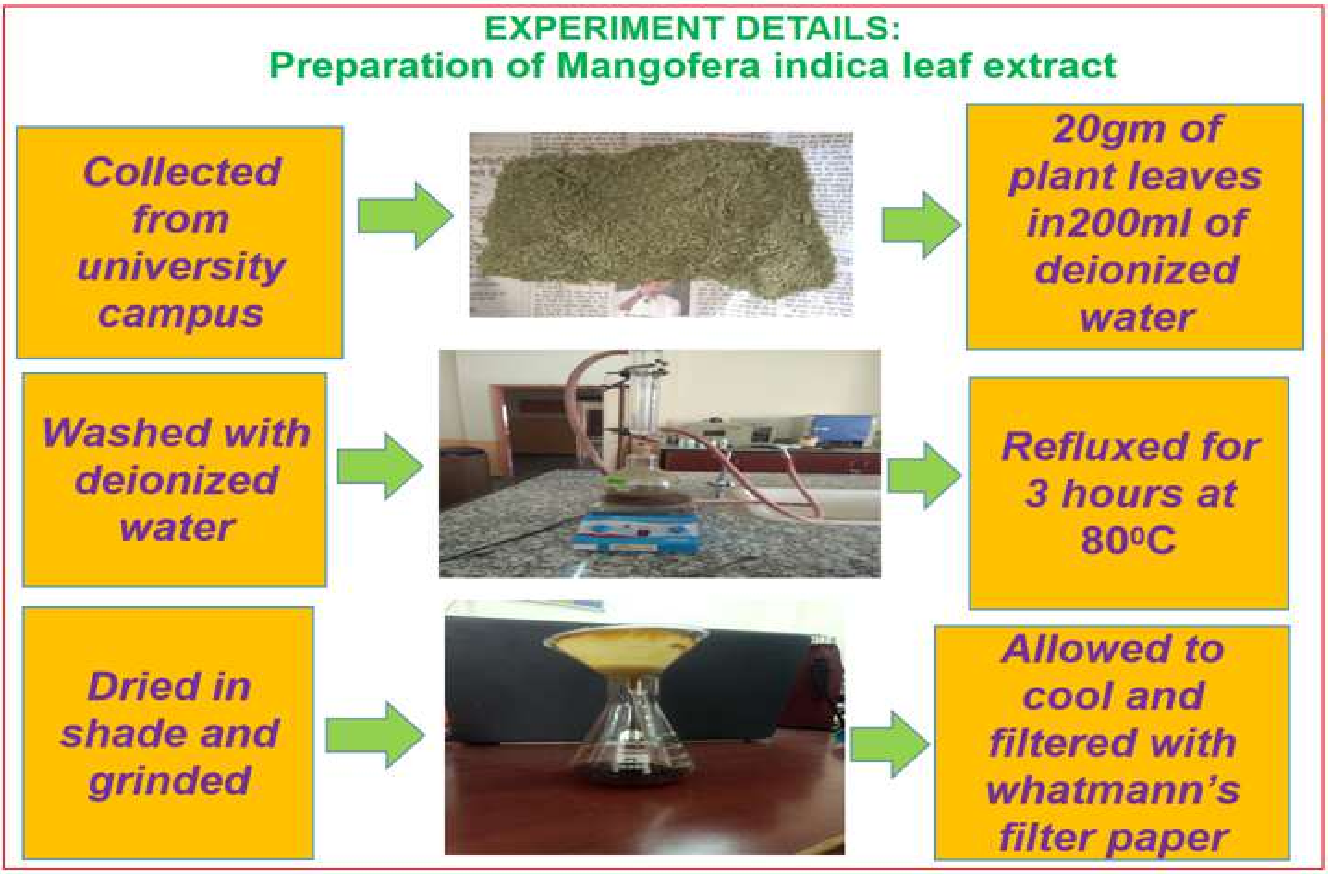

Fig 2: Preparation of Mangifera indica (M. indica) Green Leaves Extract

2.2. Preparation of the Cu/MgO nanocomposite by using the leaf aqueous extract of the Magnifera indica leaf:

CuO/MgO nanocomposites (CMNCs) were made environmentally friendly by disintegrating 2.56 grams of magnesium nitrate and 2 grams of copper acetate dihydrate in 100 ml of the deionized water, respectively.During a 250 mL round bottom flask, mix 40 mL of each solution while stirring. Afterwards the solution-based mixture attained 80^0C, then 40 mL of M. indica leaf extract was inserted dropped-wise despite being vigorously stirred subsequently for 30 minutes, then the flask was subsequently filled with a 2N sodium hydroxide solution to achieve a pH of 10. As a result, the solution was heated and swirled repeatedly until a dark brownish precipitate appeared. The colored suspended product was then cooled and vigorously centrifuged at 8000 rpm around for 5 minutes in order to isolate the CMNCs.

To remove any of the residual NaOH and extract, the precipitated material was cleansed extensively along with ethanol five or six times before being dried out four hours at 200°C in an electric oven. The subsequently dried precipitate was finally calcined during two hours at 400C in a muffle furnace in order to obtain a brownish-black powder.

Moreover, the desired CMNCs solution had been stored for future research.The synthesized material sample was analyzed utilizing various physicochemical strategies, which included

UV-vis, FT-IR, TEM, XRD,XPS and TGA. CuO and MgO nanoparticles have been produced from M.indica green leaves in order to assess their antimicrobial activity with CM NCs **[Fig 3]**.

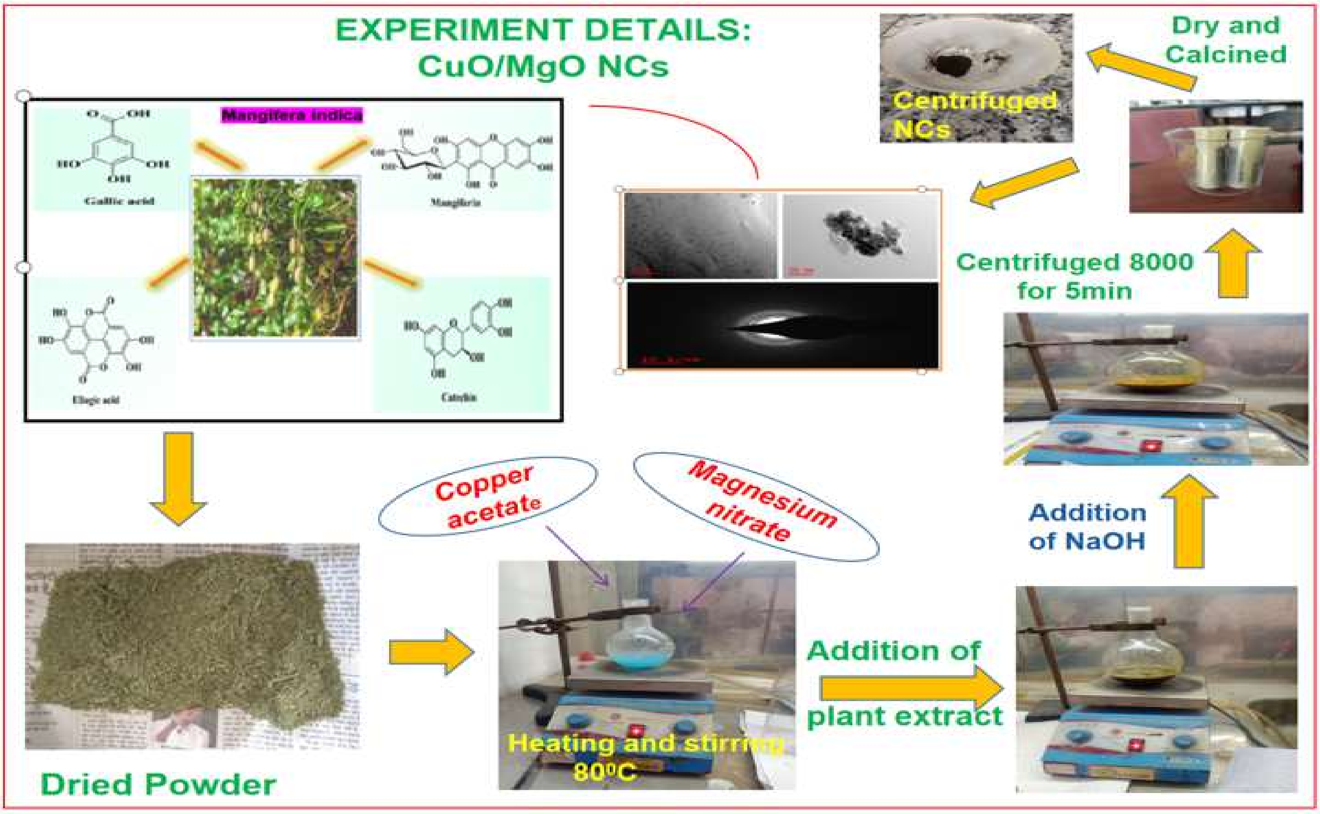

Figure 3:Schematic diagram of the green synthesis of CuO/MgO nanocomposite.

2.3. Antimicrobial experiment methodology:

CuO/MgO nanocomposite formed from M. indica extract of leaves reported antimicrobial activity towards the fungi A. niger and Penicillium, along with the bacteria S. aureus. and E. coli. The proposed in-vitro antimicrobial assay had initially been carried out using the Agar Well Diffusion method, i.e. general microbe-based laboratory technique.In addition to using nutrient agar to assess antibacterial activity, **Potato Dextrose Agar (PDA)** was utilized for assessing antifungal activity. In order to evaluate the antimicrobial activity, the sample was then dispersed in the presence of dimethyl sulphoxide (DMSO) in four various concentration levels (50 mg/L, 100 mg/L, 150 mg/mL, and 200 mg/mL) with the synthesized CuO/MgO nanocomposite solution.

In this experiment, bacterial species were introduced into sterilized petri dishes that contained nutrient agar (NA) medium for antibacterial activity and **potato dextrose agar** for antifungal activity.The microbial inoculum was evenly dispersed throughout the dish using the spreader tool and then left to stand for 30 minutes. Seeded agar plates may have been made with 6 mm diameter wells. Another petri plate was treated with the standard drug in similar concentrations. Seeded plate wells were pre-organized and filled with various sample concentrations and a standard drug (30 µl per well).

To assess antibacterial and antifungal properties, the agar plates were placed in incubators for 24 hours at 37°C. A filter paper with a disc containing **ezythromycin** (for bacterial strains) and

ketoconazole (for fungal strains) were inserted into plates containing agar as a positive control drug in order to assess antimicrobial activity.To estimate the antibacterial spectrum of the test sample, an inhibitory zone (IZ) has been formed comprised of each prepared microbial cell.The antimicrobial efficacy of CMNC has been evaluated via measurement of the zone of inhibition encompassing a filter paper disc. An average of three replicates for each experiment is depicted in **Table 1**.

2.4. Characterization:

FTIR spectral evaluation was employed to explore the impact of phytochemical compounds derived from M.indica green leaves extract in facilitating the formation of CuO/MgO NCs.A Perkin-Elmer spectrophotometer (MNIT, Jaipur) has been employed in order to carry out the evaluation in the wavenumber spectrum of 4000-400cm^{-1}.Transmission electron microscopy as well as UV-visible spectroscopy have been conducted at MNIT in Jaipur (Perkin-Elmer spectrophotometer, Lambda 750). The prepared sample was tested powder-based X-ray diffraction (PXRD) analysis at IIT Roorkee using a Rigaku X-ray diffractometer in order to determine the crystallite sizes and phase composition. At IIT Roorkee, the chemical state of elements in CMNC was assessed using X-ray photoelectron spectroscopy (XPS) using a PHI 5000Versa Probe III. The CuO/MgO sample's thermal stability has been determined in a nitrogen-based atmosphere at a heating rate of 5°C min^{-1} through the use of a TGA/DTA analyzer at MNIT, Jaipur (Perkin-Elmer spectrophotometer STA6000).

3. Results and discussion

3.1. UV-visible spectum:

The UV-vis spectrum of green synthesized CuO/MgO NCs comprising plant-based extract are displayed in the **fig. 4** revealed significant shifts in 2 absorbance peak values at 205 nm and 257 nm.**[40,41,42]**

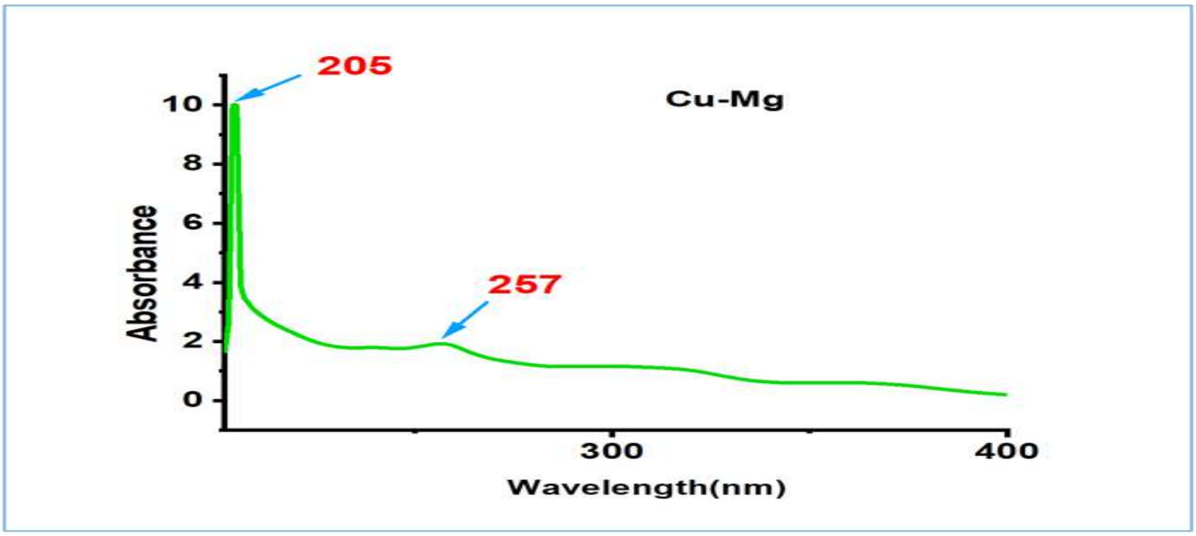

Figure 4: UV-Vis spectroscopy of CuO/MgO NCs.

3.2. Fourier transform infrared (FTIR) spectroscopy:

FTIR spectroscopy was used to examine various potential functional group structure of phytochemical components found in M.indica leaf extract and their effect on the formation of CuO/MgO nanocomposites.The synthesised sample using M.indica leaf extract is shown in **[Fig.5]**.The KBr pellet approach was employed to identify the FTIR spectrum of the synthesized material in the 4000-400 cm^{-1} region. It is prominent that the overall appearance of the distinctive peak values of the O-H (str.), C-H (str.), C=C of aromatic ring structure, and C-O stretching of carboxylic compounds are responsible for the absorption peaks approx. at 3320 cm^{-1},2916 cm^{-1} 1584 cm^{-1}, 1400 cm-^{1}, and 1042 cm^{-1}.These peak values suggested that polyphenolic compounds which had been employed in the synthesis of the nanocomposite (CuO-MgO).

According to the study's findings, the biomolecules in the extract of leaves serve as a green reducing and capping agent during the nanoparticle synthesis process.The distinct infrared peak at **544^{-1} cm** had been recognized and confirmed to be Cu-O bond stretching vibrations **[43, 44]**, and a sharp IR band at **838 cm^{-1}** was detected, which was ultimately attributed to Mg-O bond stretching vibration. **[45,46]**.

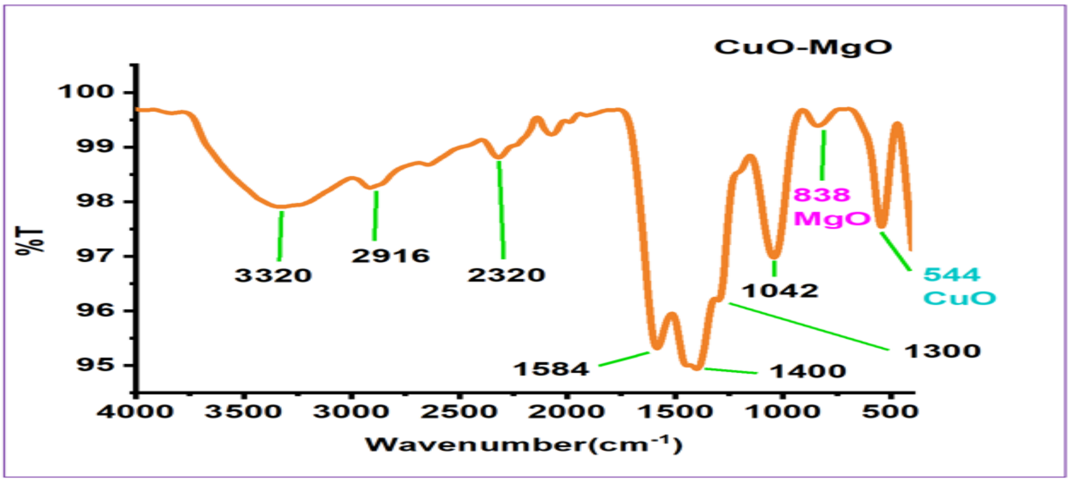

Fig. 5. FTIR spectrum analysis of a biosynthesized CuO/MgO nanocomposite.

3.3. Morphological study:

The TEM images of CMNCs in **[Fig.6(a)(b)]** clearly illustrate two distinct particle shades. CuO's strong magnetic elements indicate the existence of black particles exhibiting some agglomeration, and there is also MgO encompassing CuO in light-colored particles.The TEM images confirmed that the particles are actually between 20 to 50 nm in size. The HRTEM image also demonstrates the interface form between the CuO and MgO particles within the resulting hetero nanostructures.These TEM research findings are compatible with the formation of nanoscale size CMNCs.

Furthermore, the polycrystalline chemical composition of the nanocomposites can be observed by the selected area electron diffraction (SAED) image of CMNCs which is exhibited in **[Fig.6(c)]**,further demonstrating the fabrication of bimetallic composites.**[47,48]**

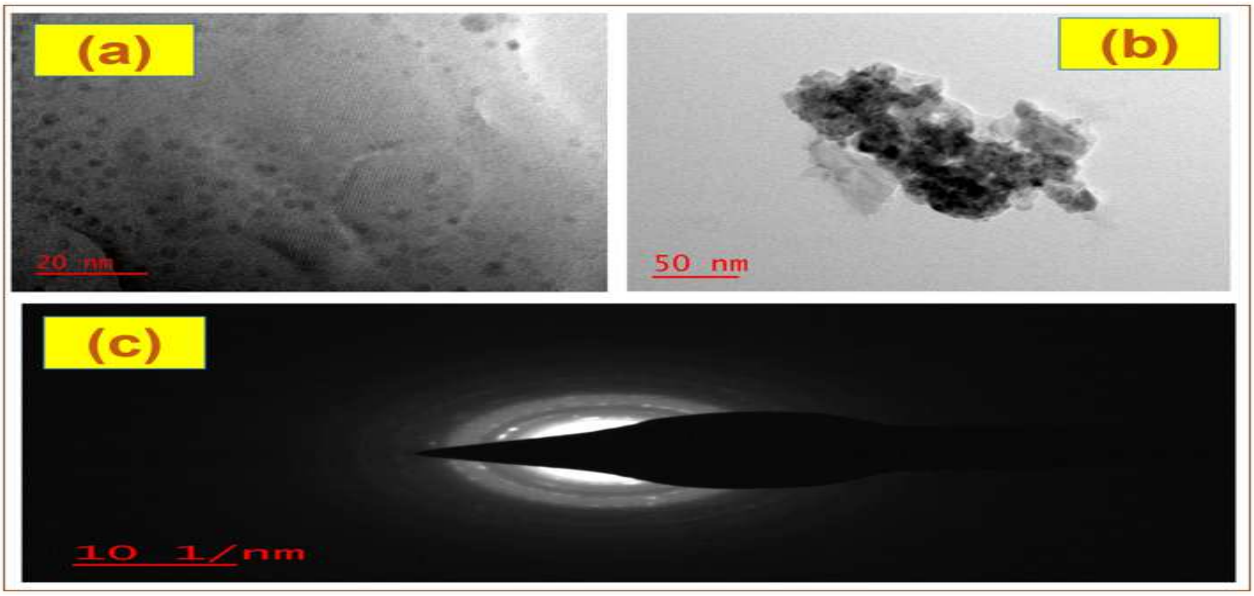

Figure 6: TEM images (a,b) of CuO/MgO NCs at different magnification and (c) SAED pattern of CM NCs

3.4. Powder XRD study:

XRD analysis, most significantly efficient method for determining the crystalline structure, was implemented to analyze the resulting sample. The crystalline structure of the CuO/MgO NCs that was freshly prepared and has been determined by utilizing XRD analysis.The (111), (200), (220) and (311) planes of cubic structured magnesium oxide are reflected by diffraction peaks at 35.58°, 43.36°, 61.32° and 74.08°, respectively. These correspond to (JCPDS file no. 89-7746) **[49]**.

Compared to this, Bragg's peaks at 33.14°, 35.58°, 38.74°, 50.44°, 56.48, 58.38°, 61.32°, 66.08°, and 74.08° indicate that CuO is present in the green synthesized sample. The reflection planes (110), (-111), (111), (-202), (020), (202), (-113), (022), and (-312) **[50]** of cubic phased CuO (JCPDS file no.000-481548) have all been represented by these peaks **[Fig 7]**.In addition to MgO and CuO, the CM NCs' XRD pattern exhibited no distinctive peaks. Moreover, by using Debye-Scherrer's formula, the dimension of the crystallite of the strongest peak has been determined to be 37.01 nm. The aforementioned variables XRD results show the fabrication of pure and polycrystalline CuO/MgO nanocomposites.

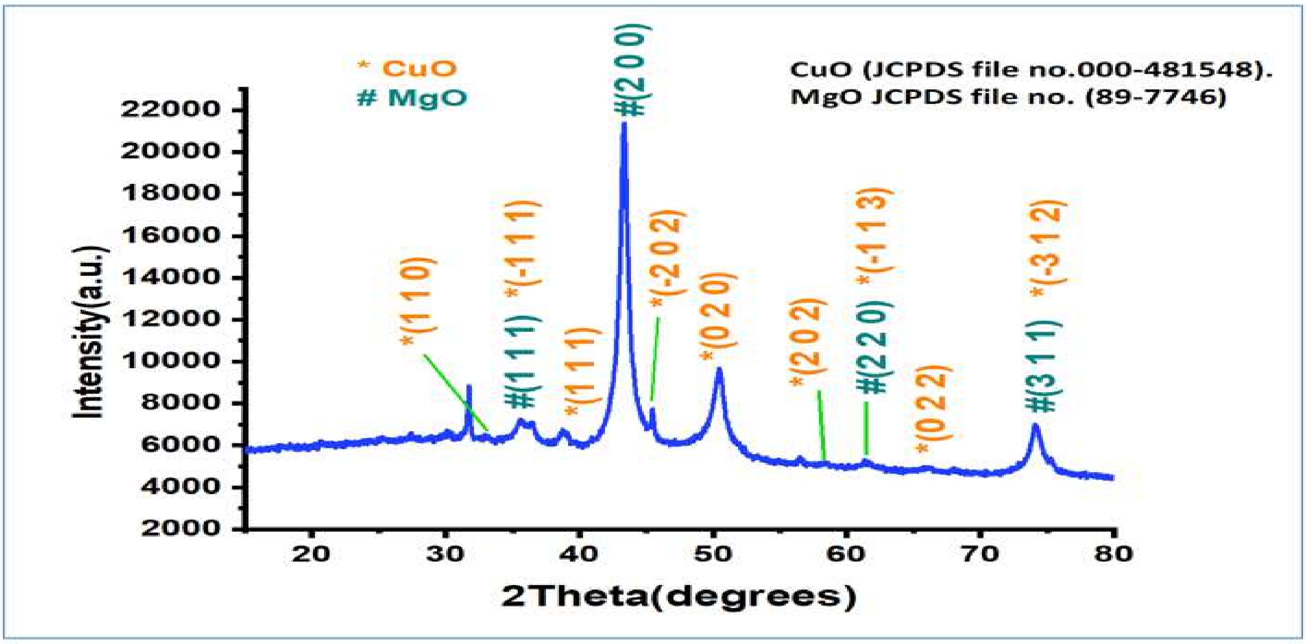

Figure 7: Powder XRD pattern biosynthesized CuO/MgO nanocomposite.

3.5. X-ray Photoelectron Spectroscopic (XPS) analysis:

The XPS assessment of CMNCs, shown **in Fig.8(a-e)**, was executed in order to display the element chemical state corresponding to the biologically prepared sample.**Figure 8(a)**depicts the full scan spectral analysis of Mg, Cu, O, and C-based CM NCs. **Figure 8(b-f)** illustrates a high resolution XPS spectrum of Mg_{2s}, Mg_{2p}, Cu_{2p},O_{1s}, and C_{1s}. **Figure 8(b and c)** shows peaks at binding energy values of 88 eV and 49.8 eV, corresponding to peaks for Mg_{2s} and $Mg2_p$, which signify the Mg^{2+} state of magnesium in CuO/MgO **[51,52]**.

The Cu_{2p} spectra stated two distinctly different peak values for $Cu2p_{3/2}$ and $Cu2p_{1/2}$ (spin-orbit doublet) at binding energy values of 932.7 eV and 952.6 eV. This clarifies that copper in the CuO/MgO composite has a corresponding divalent oxidation state. The formation of nano-crystalline CuO/MgO NCs may take place when two Cu_{2p} peaks split by 19.9 eV **[53]**.**[Fig. 8(d)]**.The divalent (O^{-2}) state of oxygen in the corresponding sample**[54]** has been demonstrated as a result of the existence of O_{1s} at binding energy 530.55 eV **[Fig 8(e)].**

Furthermore, the peak in the XPS spectrum of C_{1s} is identified at 284.4 eV (C=C)**[55, 56] [Fig. 8(f)]**. The hydrocarbons of biomolecules that are that are utilized as a capping agent in nanocomposites might be responsible for the formation of these carbon peaks.The resulting development of nano-size bimetallic oxides of magnesium and copper has been strongly confirmed by the XRD and XPS analysis results.

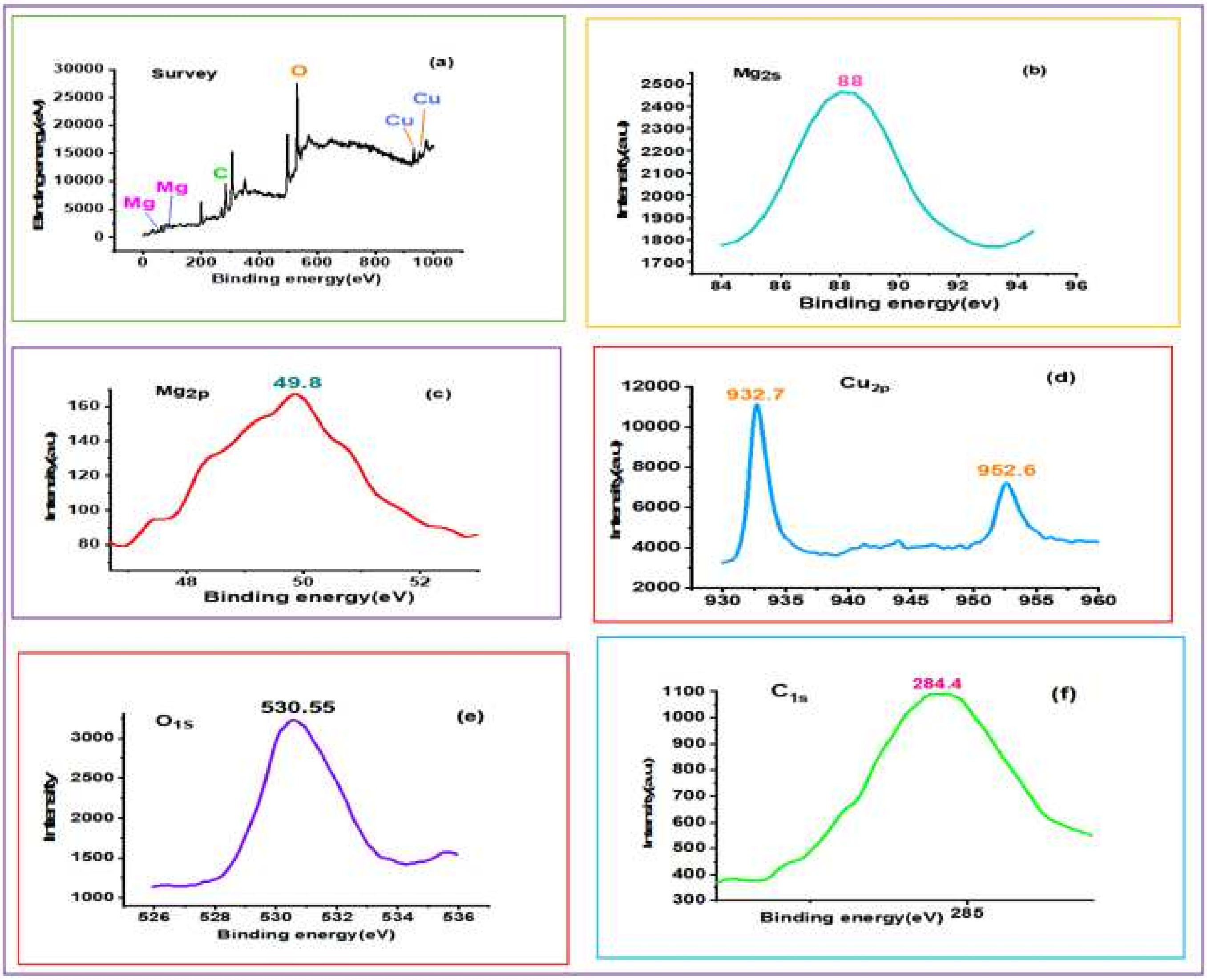

Figure 8: XPS spectra of CuO/MgO NCs (a) Survey spectrum (b) Mg2s (c) Mg2p (d) Cu2p (e) O1s (f) C1s

3.6. Thermal analysis:

The CuO/MgO nanocomposite's thermal properties that have been investigated while concurrently under similar conditions using TGA, DTA, and DTG techniques. The sample weight decreases from 100% to about 40% as the temperature increases to 800^{0}C, in accordance to the TGA/DTG graphs in **Fig 9**, which represents a major weight loss.

According to DSC, an endothermic drop(**blue line**) as well as a slight loss of weight between 50^{0}C and 150^{0}C are most likely caused by the evaporation of water absorption or residual solvents.In the first step,a major sharp peak **(red line)** at 250^{0}C and a corresponding decline in the **black line** signify the most significant thermal degradation of organic constituents.In the second step, between 400^{0}C-600^{0}C The loss of weight stabilization occurs (black curve flattens), however the blue curve highlights an extensive exothermic region, which is frequently associated with crystallization or phase transformation of the compound (CuO/MgO).On the other hand, the weight will decrease slightly in the third step, above 600^{0}C, eventually reaching a stable residual mass that is nearly equal to 800^{0}C**[57].**This can be utilized in environmentally friendly applications such as degrading organic contaminants, as well as eliminating hazardous metals from waste water during further research.

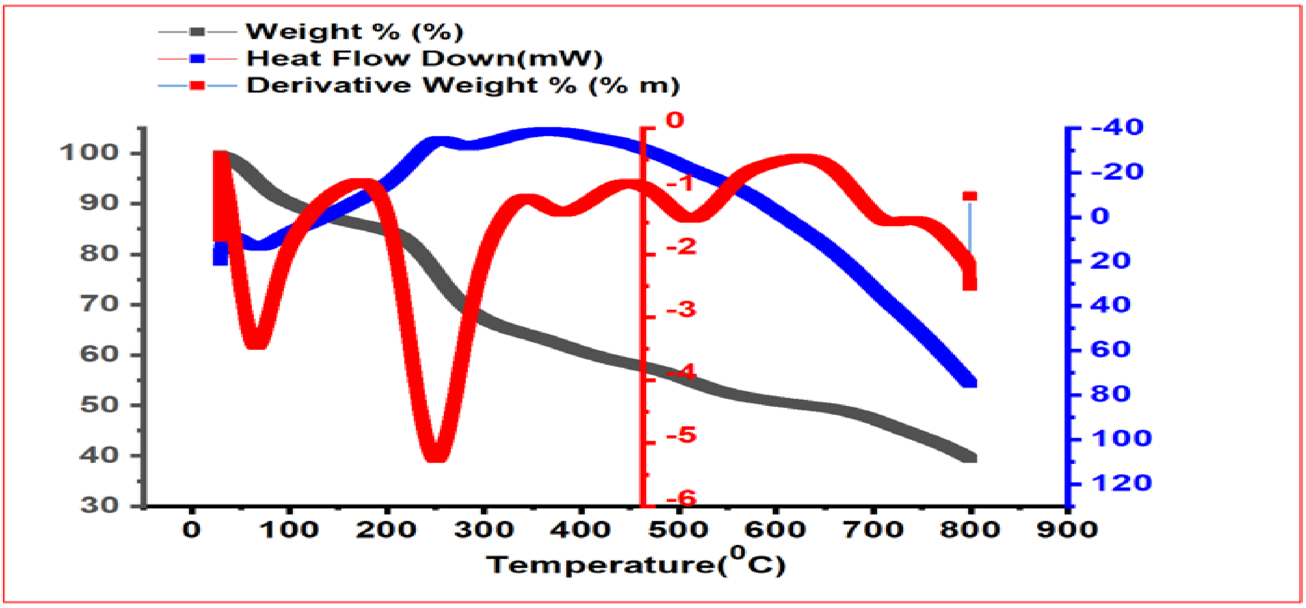

Fig. 9. TGA/DTA/DTG graphs of CuO/MgO NCs

3.7. Antimicrobial study:

The literature that has been reviewed on CuO-MgO nanocomposites concludes that these nanocomposites have been extensively used in numerous domains, which have included photocatalysis processes and conventional gas sensors applications etc,whereas their biological utility has garnered fewer considerations.James Jacob et al. reported that CuO/MgO composites displayed antimicrobial activity against pathogenic strains of bacteria such as B. subtilis, E. coli, P. aeruginosa, and S. aureus**[58]**,who further asserted that as the concentration of these strains was increased, the resulting composite's inhibitory action was enhanced.**Table.1** and **Fig. 10** show the outcomes of an in vitro test of biosynthesized nanomaterial.

CuO/MgO nanocomposites mediated through M.indica extract against E. coli and S. aureus. Inhibitory zone (death zone) values in millimeters have been utilized to illustrate inhibitory performance.According to the literature **[59,60]**, it has been demonstrated through inhibitory zone values that the antimicrobial activity of the synthesized composite increases as the concentration of CMNCs increases. Additionally, it is clear that the synthesized nanocomposite has a higher potential for bacterial strain.The structural differences between the cell walls of bacterial and fungal strains have been the cause of the variation in inhibition activity.The CuO/MgO nanocomposite inhibits both E.coli and S. aureus microbial strains **[Fig. 10.]** illustrates that S. aureus (Gram + ve bacteria) was more strongly influenced by the nanocomposite (inhibition zone 40 mm at 200 µg/ml) compared to E.coli (Gram -ve bacteria) (inhibition zone 39 mm at 200 µg/ml), maybe due to differences in chemical composition of bacterial strain.

This increase in antibacterial effect might represent an outcome of more reactive species (O2–,OH–,H_2O_2) forming on the external surface of CMNCs as the concentrations rise. These species penetrate bacteria via reacting with surface protein molecules of the bacterial cell wall **[61,62]** and even leading to microbial death by disrupting interaction with bacterial functions.

Table 1(a,b) : Antibacterial Activity of Mangifera indica-Mediated CuO/MgO Nanocomposites Against Escherichia coli and Staphylococcus aureus.

(a)

Inhibition Zone(mm)
(Test Sample)

Bacterial Strain	50 µg/ml		100 µg/ml		150 µg/ml		200 µg/ml	
E.coli ***(MTCC119)***	IZ	AI	IZ	AI	IZ	AI	IZ	AI
CuO/MgO	12	0.38	15	0.46	20	0.57	24	0.61
Standard(Inhibition Zone) mm	31		32		35		39	

(b)

Bacterial Strain	50 µg/ml		100 µg/ml		150 µg/ml		200 µg/ml	
	Inhibition Zone(mm) (Test Sample)							
S.aureus ***(MTCC3103)***	IZ	AI	IZ	AI	IZ	AI	IZ	AI
CuO/MgO	7	0.21	13	0.39	10	0.28	16	0.4
Standard(Inhibition Zone) mm	32		33		35		40	

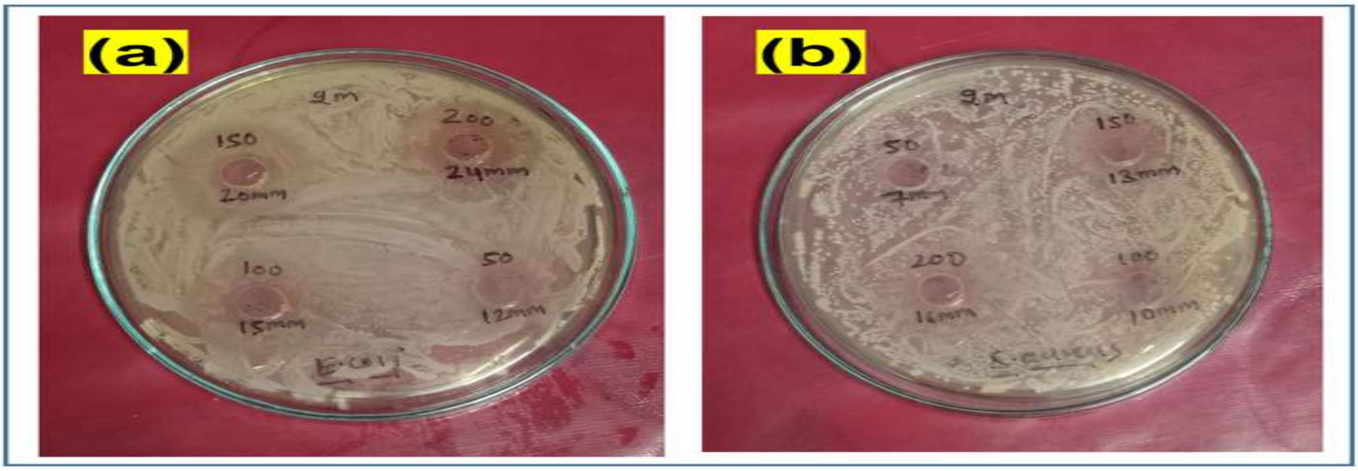

Fig. 10. Antibacterial activity of CuO/MgO nanocomposite against (a) E. coli and (b) S. aureus.

Moreover, the antifungal activity outcomes displayed in **Fig. 11** and **Table 2** indicate that both A. niger and P. chrysogenum fungal strains are inhibited by the CuO/MgO nanocomposite's zone of inhibiting effect for ketoconazole is used as a standard. According to this figure, the resulting nanocomposite had a stronger effect on P. chrysogenum via an inhibition zone of 26 mm (200 µg/ml) in comparison to A. niger via an inhibition zone of 19 mm at (200 µg/ml). The aforementioned could have been explained by differences in chemical composition of the fungal strain.

This implies that the CMNCs produced from M.indica leaf extract has very strong antibacterial properties **(S. aureus 40mm>E. coli 39mm)**. Additionally, it is evident from the data in **(Tables 1 and 2)** that biosynthesized nanomaterials are more effective against bacterial strains in comparison to fungal strains.The current research of antimicrobial activity suggests that CuO/MgO nanocomposite mediated via M.indica leaf extract could be an appropriate alternative bacterial disinfecting agent in the foreseeable future.

Table 2(a,b) : Antifungal Activity of Mangifera indica-Mediated CuO/MgO Nanocomposites Against Aspergillus niger and Penicillium chrysogenum

(a)

Fungal Strain	Inhibition Zone(mm) (Test Sample) 50 µg/ml		100 µg/ml		150 µg/ml		200 µg/ml	
	IZ	AI	IZ	AI	IZ	AI	IZ	AI
A.niger ***(MTCC13111)***								
CuO/MgO	7	0.46	8	0.5	10	0.58	14	0.73
Standard(Inhibition Zone) mm	15		16		17		19	

(b)

Fungal Strain	Inhibition Zone(mm) (Test Sample) 50 µg/ml		100 µg/ml		150 µg/ml		200 µg/ml	
	IZ	AI	IZ	AI	IZ	AI	IZ	AI
Penicillium chrysogenum- ***(MTCC1996)***								
CuO/MgO	7	0.31	7	0.29	13	0.52	15	0.57
Standard(Inhibition Zone) mm	22		24		25		26	

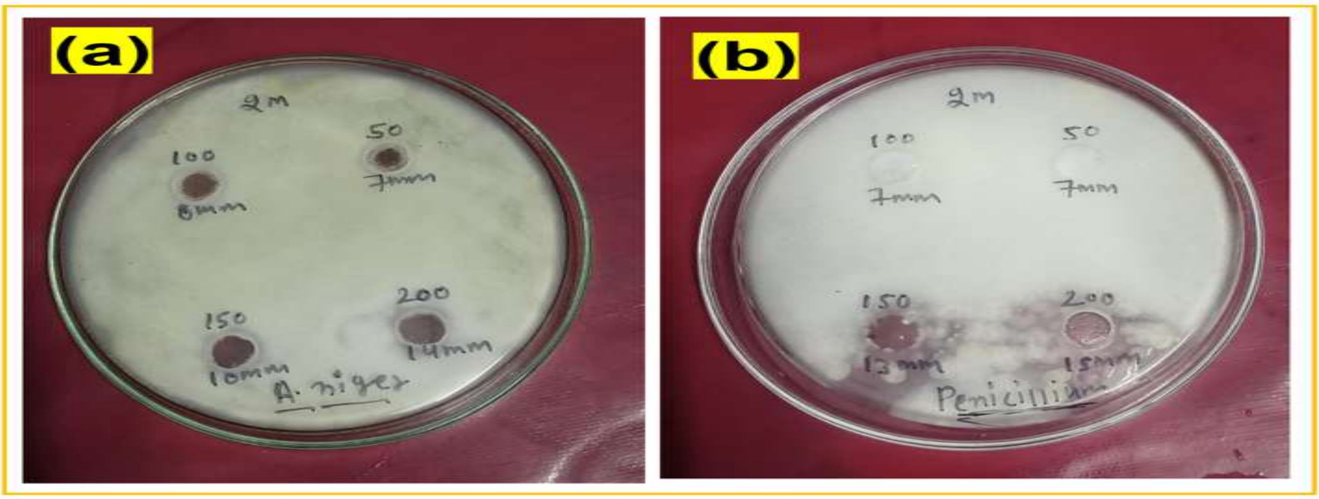

Fig. 11. Antifungal activity of CuO/MgO nanocomposite against (a) A.niger and (b) P. chrysogenum.

4. Conclusion:

In the final analysis, a green, economically feasible, and environmentally conscious approach has been effectively implemented to fabricate CuO/MgO nanocomposites. The formation of the nanocomposites was validated by the bimetallic oxide CuO/MgO nanocomposites, which showed the UV-Vis absorbance intensity at 205 and 257 nm. M.indica leaf extract biomolecules have been involved in both the reduction and capping regarding magnesium and copper ions, which results in CMNCs, according to FTIR analysis. TEM analysis was used in order to verify the presence of Cu and Mg in the composite material. According to XRD analysis, the nanoparticles were polycrystalline. CuO/MgO heterojunction formation is confirmed by XPS analysis. TGA and DTA had been utilized to assess the thermal viability of NCs in a nitrogen atmosphere.

Moreover, compared to their corresponding CuO or MgO nanoparticles, the CuO/MgO nanocomposite formed from M.indica leaf extract might prove more potent at inhibiting microbial growth strains. Consequently, the current work implies an appropriate framework for the economically viable, ecologically sustainable, and biologically synthesis of copper/magnesium based nanocomposites, as well as their potential utilization in biological, cellular, photocatalytic processes, and many other fields for further investigation.

Acknowledgement

We expressed our gratitude to the Centre for Research, Instrumentation & Development (CRID) at Poornima University in Jaipur for their assistance. The Poornima University administration's seed money grant greatly aided in the effective completion of this research project. Preetam Singh acknowledges the research environment and motivational support from management of Jaipur National University, Jaipur

Availability of data and materials

The correct structure details entered as specified in the experimental details section, can reform the alloys described in this work. On reasonable request, the corresponding author can additionally provide data on these findings.

Conflict of Interests

We stated that the contract does not contain any personal conflicts of interest, including financial interests, personal activities, or government agencies.

Funding information

We announced that Poornima University has provided us with financial aid in the form of seed money.

Contributions from the Author's

After reviewing the article, Shiva Soni wrote the main portion on the findings and Vivek Kumar Jain evaluate and analysed the data, and Preetam Singh use the data to construct Figures 1–11, and explain the results. All authors reviewed the manuscript.

Ethics declaration: Not applicable.

Reference:

1. V. Chandrakala, V. Aruna, G.Angajala, Review on metal nanoparticles as nanocarriers: Current challenges and perspectives in drug delivery systems,Emergent Mater,5(2022) 1593–1615. https://doi.org/10.1007/s42247-021-00335-x

2. K. Chaloupka , Y.Malam , A.M. Seifalian, Nanosilver as a new generation of nano product in biomedical applications, Trends Biotechnol, 28(2010):580-588. doi:10.1016/j.tibtech.2010.07.006

3. S. Camelio, D. Babonneau, A.Declemy, E. Fonda, A.Traverse, T. Girardeau, Relations between the optical properties of Cu-Ag:Si3N4 nanocermets and the microstructure of the metallic nanoclusters, JNON-CRYSTSOLIDS, 352(2006)2501-2505 doi: 10.1016/j.jnoncrysol.2006.02.065

4. R. Renuka, K. R. Devi, M.Sivakami, T. Thilagavathi R. Uthrakumar, K. Kaviyarasu,Biosynthesis of silver nanoparticles using phyllanthus emblica fruit extract for antimicrobial application, Biocatal. Agric. Biotechnol, 24(2020)101567. doi: 10.1016/j.bcab.2020.101567

5. D. Zhang, X. Liu, Synthesis of polymer stabilized monometallic Cu and bimetallic Cu/Ag nanoparticles and their surface enhanced Raman scattering properties. J Mol Struct, 1035 (2013) 471-475. doi: 10.1016/j.molstruc.2012.12.023

6. A. Heidari, Applications of single-walled carbon nanotubes(SWCNT) in the production of Glucose Biosensors and improving their performance using Gold colloidal nanoparticles and usage of polyaniline nanostucture-Based Biosensors for dectecting Glucose and cholestrol, Malays J Chem, 22(2020)121-162. doi: 10.55373/mjchem.v22i2.610

7. H.M.Yusop, W.N. W. Ismail, A review on synthesis of plant mediated metal nanoparticles for fabric coating. Malays J Chem, 23 (2021) 40-54. doi: 10.55373/mjchem.v23i2.997

8. S.Vimalraj,T. Ashokkumar, S. Saravanan, Biogenic gold nanoparticles synthesis mediated by Mangifera indica seed aqueous extracts exhibits antibacterial, anticancer and antiangiogenic properties, Biomed. Pharmacother, 105(2018)440–448. doi: https://doi.org/10.1016/j.biopha.2018.05.151

9. A. Jayachandran, T.R. Aswathy, A.S. Nair, Green synthesis and characterization of zinc oxide nanoparticles using Cayratia pedate leaf extract, Biochem. Biophys. Rep. 26(2021) 100995. https://doi.org/10.1016/j.bbrep.2021.100995

10. C. Burda, X. Chen, R. Narayanan, M.A.El-Sayed, Chemistry and properties of nanocrystalsof different shapes, Chem. Rev, 105(2025)1025–1102. https://doi.org/10.1021/cr030063

11. R. Ferrando, J. Jellinek, R.L. Johnston, Nanoalloys: From theory to applications of alloy clusters and nanoparticles, Chem. Rev,108 (2008) 108, 845–910. https://doi.org/10.1021/cr040090g

12. J.A. Rodriguez, D.W.Goodman, The nature of the metal-metal bond in bimetallic surfaces. Science, 257(1992) 897–903. DOI: 10.1126/science.257.5072.897

13. F. Tao, M.E.Grass, Y. Zhang,D.R. Butcher, J.R. Renzas, Z.Liu, J.Y. Chung, B.S. Mun, M. Salmeron, G.A. Somorjai, Reaction-driven restructuring of Rh-Pd and Pt-Pd core-shell nanoparticles, Science, 322(2008), 932–934. DOI: 10.1126/science.1164170

14. G. Rajagopal, M. Manivannan, M. Sundararajan, A.G.Kumar, S. Samuthirarajan, N. Mathivanan, S. Ilango, Biocompatibility assessment of silver chloride nanoparticles derived from Padina gymnospora and its therapeutic potential, Nano Express,2(2021) 010010.DOI 10.1088/2632-959X/abd965

15. R. Gupta, H. Xie, Nanoparticles in daily life: Applications, toxicity and regulations, J. Environ. Pathol. Toxicol. Oncol, 37(2018) 209–230.DOI: 10.1615/2018026009

16. R. Ishwarya, B. Vaseeharan, R. Anuradha, R. Rekha, M.Govindarajan, N.S.Alharbi, S. Kadaikunnan, J.M. Khaled, G. Benelli, Eco-friendly fabrication of Ag nanostructures using the seed extract of Pedalium murex, an ancient Indian medicinal plant:Histopathological effects on the Zika virus vector Aedes aegypti and inhibition of biofilm-forming pathogenic bacteria,J.Photochem.Photobiol.BBiol,174(2017)133-143. https://doi.org/10.1016/j.jphotobiol.2017.07.026

17. A. Folorunso, S. Akintelu, A.K. Oyebamiji, S. Ajayi, B. Abiola, I. Abdusalam, A. Morakinyo A. Biosynthesis Characterization and antimicrobial Activity of gold nanoparticles from leaf extracts of Annona muricata J. Nanostru. Chem, 9(2019) 111-117.https://doi.org/10.1007/s40097-019-0301-1

18. R. Prasanth, S. D. Kumar, A. Jeyalakshmi, G. Singaravelu1, K.Govindaraju, V.Ganesh Kumar, Green synthesis of magnesium oxide nanoparticles and their antibacterial activity,Indian J. Geo-Mar. Sci., 48 (2019) 1210-1215.

19. S.A. Akintelu, A.S. Folorunso, O.T. Ademosun , Instrumental characterization and antibacterial investigation of silver nanoparticles synthesized from Garcinia kola leaf, J. Drug Deliv, 9 (2019) 58-64. DOI:10.22270/jddt.v9i6-s.3749

20. A.S. Akintelu, F.A. Similoluwa,Biosynthesis, characterization and antifungal investigation of Ag-Cu nanoparticles from bark extracts of garcina kola, Stm. Cell, 10 (2019) 30-37. DOI:10.7537/marsscj100419.05

21. S.A. Akintelu, A.S. Folorunso Characterization and antimicrobial investigation of synthesized silver nanoparticles from Annona muricata leaf extracts, J Nanotechnol Nanomed Nanobiotechnol, 5 (2019) 1-5.DOI: 10.24966/NTMB-2044/100022.

22. S.A. Akintelu, A.S. Folorunso. A.K. Oyebamiji, E.A. Erazua Antibacterial potency of silver nanoparticles synthesized using Boerhaavia diffusa leaf extract as recuctive and stabilizing agent. Int. J. Pharmaceut. Sci.Res, 10(2019) 374-380.

23. M. Nasrollahzadeh, S. Mahmoudi-Gom Yek, N. Motahharifar, M.G. Gorab, Recent developments in the plant mediated green synthesis of Ag based nanaoparticles for environmental and catalytic applications chem, A Journal of the Chemical Society of Japan, 19 (2019) 2436-2479.

24. P.P.N.V. Kumar, S. V. N. Pammi, P. Kollu, K.V.V. Satyanarayana ,U Shameem,Green synthesis and characterization of silver nanoparticles using Boerhaavia diffusa plant extract and their anti bacterial activity, Industrial Crops and Products,52 (2014) 562-566. doi: 10.1016/j.indcrop.2013.10.050

25. S. K. Moorthy , C.H.Ashok, K. V. Rao, Synthesis and characterization of MgO nanoparticles by neem leaves through green method, Mater. Today: Proc, 2 (2015) 4360-4368. 10.1016/j.matpr.2015.10.027

26. H. Amrulloh, A.Fatiqin, W. Simanjuntak, H. Afriyani, A. Annissa, Antioxidant and antibacterial activities of magnesium oxide nanoparticles prepared using aqueous extract of Moringa oleifera bark as green agents,J MultidiscipAppl Nat Sci, 1(2021)44–53. https://doi.org/10.47352/jmans.v1i1.9

27. M.R. Bindhu, M. Umadevi, M.K. Micheal, M.V. Arasu, N.A. Al-Dhabi, Structural, morphological and optical properties of MgO Nanoparticles for antibacterial applications. Mater Lett, 166 (2016) 19–22.https://doi.org/10.1016/j.matlet.2015.12.020

28. L. Cai, J. Chen, Z. Liu, H. Wang, H. Yang, W. Ding, Magnesium oxide nanoparticles: effective agricultural antibacterial agent against Ralstonia solanacearum, Front Microbiol, 9 (2018) 1-19. https://doi.org/10.3389/fmicb.2018.00790

29. H.T. Gebrie, M.A. Assege, D.S. Meshesha, B.A. Tebeje, G.W. Moges, A.T. Wodajo, G.M. Manahelohe, A.A. Belew, Biosynthesis and characterization of copper oxide nanoparticles from Plumbago zeylanica leaf extract for antibacterial and antioxidant activities, Sci. Rep, 15 (2025) 30656. https://doi.org/10.1038/s41598-025-10700-z.

30. S. A. Rabi , A.T. Ravichandran, A.J.S. Kennedy, Green synthesis of magnesium oxide nanoparticles using neem leaves and their antimicrobial activity,Int. J. Nat. Sci., 16 (2025) 91651-91657 J. Pure Appl Microbiol,

31. J. Jacob, T. Augustine A. Prasad, B.S.M. Vithiya, M.R. Athisa, Biosynthesis of bimetallicCu-Ag nanocomposites and evaluation of their electrocatalytic, antibacterial and anti-cancerousactivity, J PureAppl Microbiol, 16(2022)955-966. https://doi.org/10.22207/JPAM.16.2.18

32. S.Iravani,J.A. Kumar, T. Krithiga, S. Manigandan, S. Sathish, A.A. Renita, P. Prakash, B. S.N.Prasad,T.R.P.Kumar, M. Rajasimman, A. Hosseini-Bandegharaei, D. Prabu, S. Crispin,A focus to green synthesis of metal/metal based oxide nanoparticles: various mechanisms and applications towards ecological approach, Green Chem,13 (2011) 2638. https://doi.org/10.1016/j.jclepro.2021.129198

33. J.A. Kumar, T. Krithiga, S. Manigandan, S. Sathish, A.A. Renita, P. Prakash, B.S.N. Pras ad, T.R.P. Kumar, M. Rajasimman, A. Hosseini-Bandegharaei, D. Prabu, S. Crispin, A focus

to green synthesis of metal/metal based oxide nanoparticles: various mechanisms and applications towards ecological approach, J.Clean.Prod, 324(2021) Article129198. https://doi.org/10.1016/j.jclepro.2021.129198

34. S. Ying, Z. Guan, P.C. Ofoegbu, P. Clubb, C. Rico, F. He, J. Hong, Green synthesis of nanoparticles: current developments and limitations, Envrion.Technol.Innov, 26(2022) Article 102336. https://doi.org/10.1016/j.eti.2022.102336.

35. A. Gour, N. K. Jain, Advances in green synthesis of nanoparticles, Artif. Cell. Nanomed, Biotechnol, 47 (2019) 844-851. doi: 10.1080/21691401.2019.1577878.

36. V. Subramanian V, Gautam, V. Raman ,S. Prahalathan, K. Ashish, Foreword in Road Beyond Boundaries: The Case of Selected Indian Healthcare Systems. Export-Import Bank of India Mumbai, 1 (2003) 7-9.

37. M. Lauricella, S.Emanuele, G.Calvaruso, M. Giuliano, A. D'Anneo, Multifaceted Health Benefits of Mangifera indica L. (Mango): The Inestimable Value of Orchards Recently Planted in Sicilian Rural Areas, Nutrients, 9 (2017) 525. https://doi.org/10.3390/nu9050525

38. E. Kumolosasi, S.N.A. Ibrahim, S.M.A. Shukri, W. Ahmad, Immuno stimulant activity of standardised extracts of Mangifera indica leaf and Curcuma domestica rhizome in mice, Trop. J. Pharm. Res,17 (2018) 77-84.

39. Y. Kabir, H.U. Shekhar, J. S. Sidhu, Phytochemical compounds in functional properties of mangoes,Handbook of Mango fruit: Production, Postharvest Science, Processing Technology and Nutrition, ch12 (2017) 237254. https://doi.org/10.1002/9781119014362.

40. M. Gopinathand, R .Subbaiya, M. Masilamani Selvam, D. Suresh, Synthesis of copper nanoparticles from nerium oleander leaf aqueous extract and its antibacterial activity, Int. J. Curr. Microbiol. Appl. Sci, 3 (2014) 814-818.

41. K.V. Pavani, N. Srujana, G. Preethi, T. Swati, Synthesis of copper nanoparticles by Aaspergillus species, Lett. Appl. Nano BioSci, 2 (2013) 110-113

42. S. Nagaraja, B. Bharati, S. Basavaraja, Green fabrication of MgO nanostructure for morphology and optical studies, J.Adv.Chem.Sci, 6(2020)674-675. 10.30799/jacs.221.2006010

43. A. Waris, M. Din, A. Ali, M. Ali, S. Afridi, A. Baset, A. U. Khan, A comprehensive review of green synthesis of copper oxide nanoparticles and their diverse biomedical applications,Inorg.Chem.Commun,123(2021)108369,https://doi.org/10.1016/j.inoche.2020.108369.

44. C.A. Paul, E.R. Kumar, J. Suryakanth, A.F. Abd El-Rehim, Analysis and characterization of structural, morphological, thermal properties and colloidal stability of CuO nanoparticles for various natural fuels, Ceram. Inter, 49(2023)31193–31209, https://doi.org/10.1016/j.ceramint.2023.07.065.

45. D. Durgalakshmi, R.A. Rakkesh, S. Kamil, S. Karthikeyan, S. Balakumar, Rapid dilapidation of alcohol using magnesium oxide and magnesium aspartate based nanostructures:

A Raman spectroscopic and molecular simulation approach, J. Inorg. Organomet. Polym. Mater, 29 (2019) 1390–1399. 10.1007/s10904-019-01105-3

46. C.W. Wong, Y. S. Chan, J. Jeevanandam, K. Pal, M. Bechelany, M.A. Elkodous, G.S. El-Sayyad, Response surface methodology optimization of mono-dispersed MgO nanoparticles fabricated by ultrasonic-assisted sol–gel method for outstanding antimicrobial and antibiofilm activities, J. Clust. Sci, 31(2020) 367–389. 10.1007/s10876-019-01651-3

47. R. Khani, B. Roostaei, G.Bagherzade, M. Moudi, Green synthesis of copper nanoparticles by fruit extract of *Ziziphus spina-christi* (L.) Willd.: application for adsorption of triphenylmethane dye and antibacterial assay, J.Mol.Liq, 255 (2018) 541–549 https://doi.org/10.1016/j.molliq.2018.02.010.

48. A. Muhaymin, H.E.A. Mohamed, K. Hkiri, A. Safdar, S. Azizi, M. Maaza, Green synthesis of magnesium oxide nanoparticles using Hyphaene the baica extract and their photocatalytic activities,Sci Rep,**14** (2024)20135. https://doi.org/10.1038/s41598-024-71149-0

49. N. R. Dhineshbabu, G. Karunakaran, R. Suriyaprabha, P. Manivasakan, V. Rajendran, Electrospun MgO/Nylon 6 hybrid nanofibers for protective clothing, Nano-Micro Lett., 6 (2014) 46-54. http://dx.doi.org/10.5101/nml.

50. K. Nithya, P. Yuvasree, N. Neelakandeswari, N. Rajasekaran , K. Uthayarani , M. Chitra, S. S. Kumar Preparation and characterization of copper oxide nanoparticles, Int.J. ChemTech Res., 6 (2014) 2220-2222.

51. A. L. Febvrier, J. Jensen, P. Eklund, Wet-cleaning of MgO: Modification of surface chemistry and effects on thin film growth investigated by x-ray photoelectron spectroscopy and time-of-flight secondary ion mass spectroscopy, J.Vac.Sci.Technol.A, 35(2017) 021407. https://doi.org/10.1116/1.4975595.

52. L. Dang, X. Nai, Y. Dong, W. Li, Functional group effect on flame retardancy, thermal, and mechanical properties of organophosphorus-based magnesium oxysulfate whiskers as a flame retardant in polypropylene, RSC Adv,7 (2017) 21655–21665.

53. A. S. Ethiraj, D. J. Kang, Synthesis and characterization of CuO nanowires by a simple wet chemical method, Nanoscale Res. Lett., 7(2012)1-5. doi:10.1186/1556-276X-7-70

54. V. V. Kumar, A. Dharani, M. Mariappan, S.P. Anthon, Synthesis of CuO and Cu2O nano/microparticles from a single precursor: effect of temperature on CuO/Cu2O formation and morphology dependent nitroarene reduction, RSC Adv, 6(2016)85083-85090 https://doi.org/10.1039/C6RA16553B.

55. S. Zhan, D. Zhu, S. Ma, W. Yu, Y. Jia, Y. Li , H. Yu, Z. Shen, Highly efficient removal of pathogenic bacteria with magnetic graphene composite, ACS. Appl. Mater. Interfaces, 7 (2015) 4290–4298. https://doi.org/10.1021/am508682s

56. J. Cirone, S. R Ahmed, P. C. Wood, A. Chen, Green synthesis and electrochemical study of cobalt/graphene quantum dots for efficient water splitting., J Phys Chem C., 123 (2019) 9183–9191. doi:10.1021/acs.jpcc.9b00951

57. N. Basavegowda, K. Mishra, Y. R. Lee, Trimetallic Fe Ag Pt alloy as a nanocatalyst for the reduction of 4-nitroaniline and decolorization of rhodamine B: A comparative study, J. Alloy compd.,701 (2017) 456–464. https://doi.org/10.1016/j.jallcom.2017.01.122
58. J. Jacob,T. Augustine, A. Prasad, B.S.M. Vithiya, M.R. Athisa, Biosynthesis of bimetallic Cu-Ag nanocomposites and evaluation of their electrocatalytic, antibacterial and anti cancerous activity, J Pure Appl Microbiol, 16(2022)955-966. https://doi.org/10.22207/JPAM.16.2.18

59. R.M. Kumari, N. Thapa, N. Gupta, A. Kumar, S. Nimesh, Antibacterial and photocatalytic degradation efficacy of silver nanoparticles biosynthesized using Cordia dichotoma leaf extract, Canosci. Nanotechnol, 7(2016)045009. 10.1088/2043-6262/7/4/045009.

60. E. Ajayi, A. A. folayan, Green synthesis, characterization and biological activities of silver nanoparticles from alkalinized Cymbopogon citratus Stapf, Adv. Nat. Sci. Nanosci. Nanotechnol, 8 (2017) 015017. DOI 10.1088/2043-6254/aa5cf7.

61. E. Gopinathan, G. Viruthagiri, N. Shanmugam, R.Gobi, Synthesis and characterization of ZrO2–CuO co-doped ceria nanoparticles via chemical precipitation method, Spectrochimica ActaPartA:MolBiomolSpectrosc,131(2014)556-563.https://doi.org/10.1016/j.saa.2014.04.117.

62. A. Sirelkhatim, S. Mahmud, A. Seeni, N. H. M. Kaus, L. C. Ann, S. K. M. Bakhori, H. Hasan, D. Mohamad, Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism, Nano-Micro Lett, 7(2015) 219–242. doi: 10.1007/s40820-015-0040-x.