Letters in Applied NanoBioScience
Open-Access Journal (ISSN: 2284-6808)

Review
Volume 15, Issue 1 2026, 13
https://doi.org/10.33263/LIANBS151.013

Plant-synthesized CuO and ZnO Nanoparticles: Versatile Applications and Characterization

Jwel Sharma [1,*]

[1] Department of Chemistry, National University, Gazipur 1704, Bangladesh
* Correspondence: jewelsharma0099@gmail.com;

Received: 21.12.2024; Accepted: 24.02.2026; Published: 30.03.2026

Abstract: Nanotechnology has lately arisen as a revolutionary technology, highlighting exclusive qualities owing to heterogeneous sizes and shapes. This manuscript focuses on synthesizing, characterizing, and applying copper oxide (CuO) and zinc oxide (ZnO) NPs derived from various plant parts. These include leaves, peels, roots, seeds, fruits, and flowers. Plant-derived procedures for nanoparticle synthesis alleviate environmental pollution and minimize manufacturing costs. Furthermore, it facilitates the rising demand for green-synthesized nanoparticles. In this study, we investigate the biochemical mechanisms underlying the plant synthesis of CuO and ZnO NPs, with particular attention to their biomedical and environmental applications. Characterization techniques such as Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and Transmission Electron Microscopy (TEM), among others, were used to assess the physical and chemical properties of the NPs.Eventually, we analyze future directions for research, containing potential advancements in synthesis techniques and the investigation of new applications to boost the sustainability and performance of these NPs. The findings represent that green synthesis nanoparticles are more cost-effective, environmentally friendly, and superior compared to synthetic nanoparticles.

Keywords: green synthesis; plant synthesis; copper oxide nanoparticles; zinc oxide nanoparticles; biogenic synthesis.

1. Introduction

ZnO NPs possess several advantageous characteristics, such as UV-blocking efficiency, high stability, and photocatalytic activity, which have made them indispensable across any domains [1–3]. ZnO NPs are utilized in the electronics field to produce varistors, gas sensors, and piezoelectric devices [4]. The photocatalytic properties of ZnO NPs enable their use in environmental remediation and wastewater treatment, notably by breaking down pollutants under UV light [5]. Conversely, CuO NPs are underscored for their potential catalytic characteristics and antimicrobial activity. Copper oxide nanoparticles are profoundly utilized in catalysis, facilitating several chemical reactions associated with oxidation and reduction processes [6,7]. The antimicrobial properties of the NPs are highlighted as a promising feature for applications in medicine, notably for improving drug delivery systems and antimicrobial coatings [8].

Conventional techniques for synthesizing nanoparticles often involve physicochemical approaches that use hazardous chemicals and generate toxic by-products that pose significant environmental and health risks [9]. Enormous urbanization, industrialization, and population growth have heightened environmental concerns, necessitating the development of eco-friendly,ustainable synthesis pathways [10]. Green synthesis, notably by using plant extracts, has appeared as a pivotal alternative. Plant-based synthesis of NPs offers several advantages, such as the use of readily available, non-toxic reducing agents [11]. Numerous phytochemicals present in plant extracts, such as terpenoids, flavonoids, and phenolics, can significantly reduce metal precursors for NP formation while also providing stabilizing effects. The process not only minimizes the dependence on expensive and hazardous chemicals but also reduces the ecological footprint of NPs synthesis [12].

The mechanisms underlying the fundamental plant-extracted synthesis of CuO and ZnO nanoparticles are complex and not yet fully understood [13,14]. However, it is well established that biological molecules, such as enzymes, proteins, and polysaccharides, play a critical role in stabilizing and reducing metal ions [15,16]. For example, in the matter of ZnO NPs synthesis, the existence of organic compounds over plant extracts can simplify the nucleation and the growth of ZnO nanoparticles, inducing the design of particles with acceptable morphologies and sizes [17]. Likewise, for CuO nanoparticles, plant extracts can allow an appropriate environment that allows the reformation of Cu ions into metallic copper, which afterward oxidizes to form CuO NPs. The interaction between various biomolecules and metal ions is significant for managing the shape, size, and stability of the synthesized NPs [18].

The plant synthesis of CuO and ZnO NPs demonstrates various potential advantages. Firstly, the usage of plant extracts remarkably decreases the toxicity compared to traditional chemical synthesis techniques. This is particularly essential, given the increasing regulatory scrutiny of the use of toxic chemicals in NProduction [19]. Additionally, the eco-friendly features of green synthesis systems enable the recycling of the most expensive metal salts from waste streams, thereby promoting sustainable resource management. Furthermore, the biogenic production of nanoparticles often yields materials with increased bioactivity due to the presence of natural stabilizing agents, which can ameliorate interactions with biological systems [20,21]. In addition, the versatility of plant-mediated synthesis makes it a practical choice for the mass production of NPs. The worldwide availability of many plant species led to the exploration of several sources for NPs production, contributing to diverse applications customized to specific needs [22,23].

Characterization of the chemical and physical properties of plant-synthesized CuO and ZnO nanoparticles is essential for understanding their behavior and applications. Strategies, such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), UV-Vis spectroscopy, and X-ray diffraction (XRD), are commonly employed to measure the morphology, size, crystal structure, and optical characteristics of plant-synthesized NPs [24,25]. The shape and size of nanoparticles remarkably determine their reactivity and performance in different applications. For instance, smaller NPs often exhibit greater surface reactivity, thereby contributing to the development of antimicrobial activity [26–28]. Studies have shown that biogenic silver NPs exhibit 20 times greater antimicrobial activity than chemically synthesized counterparts. Likewise, the unique characteristics of CnO and ZnO NPs produced over green methods can lead to improved efficacy in applications such as environmental remediation and drug delivery [29].

Despite having potential progress in the synthesis of CuO and ZnO NPs, there remains a relative lack of widespread studies elucidating the biosynthesis and potential applications of other metallic and semiconductor nanoparticles. Future studies should focus on exploring the mechanisms of NPs formation and optimizing synthesis conditions to improve the yield and uniformity of the synthesized particles. Furthermore, the significant applications of CuO and ZnO nanoparticles remain enormous and warrant further exploration. In biotechnology, these NPs can be used in drug delivery methods, where their unique properties facilitate targeted delivery of therapeutic agents. In addition, their antimicrobial properties can be used in several medical applications, such as wound dressings and coatings for medical devices. Finally, the plant-based synthesis of CuO and ZnO NPs represents a sustainable and environmentally friendly approach to producing nanoparticles, while retaining the natural properties of plant extracts. Researchers can make NPs with desired properties and improved bioactivity. As the field continues to unfold, the essential applications of these NPs will certainly expand, enabling revolutionary solutions to current challenges across many industries. The main objective of the study is to thoroughly define plant-synthesized nanoparticles from various plant parts (Figure 1), including their utilization, such as antibacterial, antibiotic, biomedical, photodegradation, antioxidant, antidiabetic, antimicrobial, anti-fungal, photocatalytic, photovoltaic, anti-arthritic, anti-inflammatory, larvicidal, insecticidal, anticancer, anti-dandruff, and dye removal agents. Furthermore, their characterization has been described in detail, including sizes and characterization strategies.

This study highlights, for instance, the mechanisms of plant-based synthesis of CuO and ZnO NPs, the characterization and application strategies of ZnO and CuO NPs, and future directions and applications.

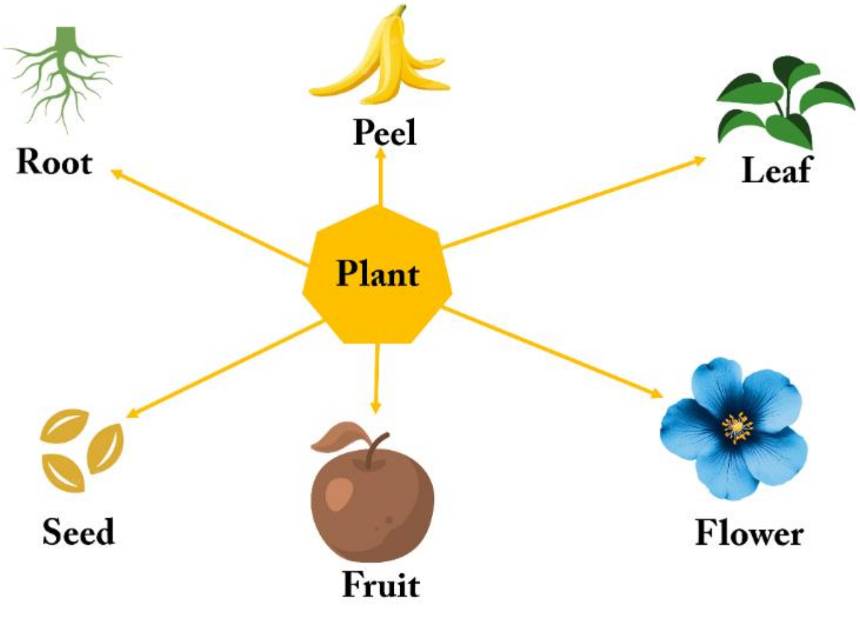

Figure 1. Sources of plants to synthesize CuO and ZnO nanoparticles.

2. Mechanisms of Plant-based CuO and ZnO NPs Synthesis Process

The synthesis of CuO and ZnO NPs using plant sources is a revolutionary, sustainable method that leverages plants' natural capabilities to manufacture NPs. This technique leverages green synthesis methods, including enzymatic reduction, metal ion absorption, and biomolecular stabilization, to produce NPs with the required attributes and also enhances environmental safety [30,31]. The primary and most important phase in plant-based synthesis is the absorption of metal ions from the culture medium via plant roots. Research has shown that different plants can successfully take up metals, such as Cu and Zn [32,33].

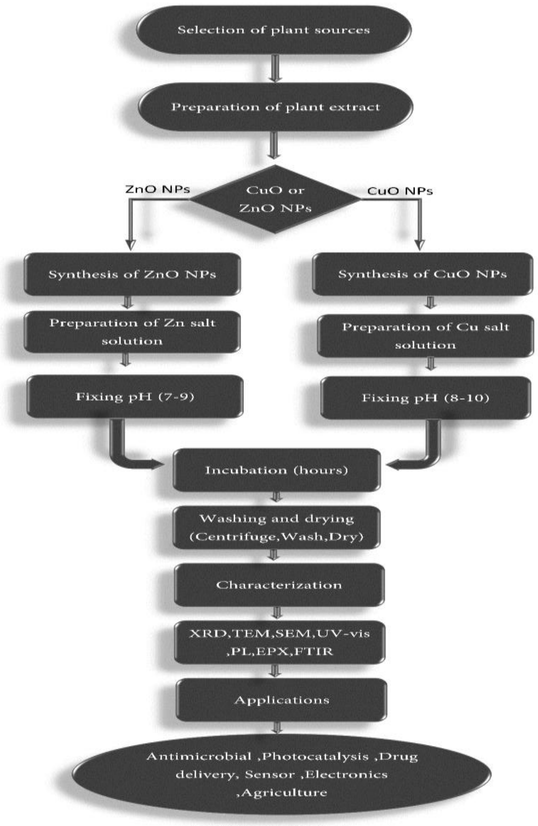

Figure 2. Strategies to synthesize CuO and ZnO nanoparticles (NPs).

After absorption, these metal ions are moved to different plant counterparts, where they sustain bioreduction. It is also facilitated by plant enzymes, like reductases, which transform metal ions into NPs [34,35]. Moreover, phytochemicals present in plant-derived materials, including terpenoids, phenols, and flavonoids, play a pivotal role in stabilizing the synthesized NPs and reducing metal ions[36].

After synthesis, the NPs are balanced by biomolecules, hindering clusters and securing stability in suspension. Capping agents derived from plant sources enhance the exclusive surface features of NPs by controlling their functionality, shape, and size. For example, the presence of polyphenols in plant extracts has been shown to enhance the antioxidant properties and stability of AgNPs [37–39].

Nonetheless, the sizes and morphologies of the NPs can be affected by various reaction parameters, such as the concentration of the reaction precursor, the plant species, and the pH of the medium. Many plant species exhibit different efficiencies in synthesizing NPs, which are mediated by their specific biochemical substances. For example, studies have demonstrated that leaf extracts from specific plants, including *Aloe vera* and *Coriandrum sativum*, can synthesize NPs with desired shapes and sizes, shifting from spherical to rod-like structures [40–42]. The synthesized NPs have numerous applications with unique attributes. For instance, plant-based Ag NPs have shown potential antimicrobial activity against various pathogens, making them applicable in medical and agricultural applications, among others[43]. Likewise, Au NPs synthesized using plant extracts have been analyzed for use in drug delivery systems and biosensors, owing to their biocompatibility and ease of functionalization [44–46].

After all, plant-based synthesis of NPs represents a pivotal alternative to traditional chemical methods, enabling greener, more sustainable practices. The mechanisms in Figure 2 that underpin this method are complex and involve multiple biological and biochemical interactions, underscoring the potential of plant-based methods for nanomaterial synthesis.

Ongoing studies into the optimization of these strategies and the properties of plant-mediated NPs will further increase their utilization in many fields, such as medicine, agriculture, and environmental science.

3. Characterization and Application Strategies of ZnO and CuO Nps

3.1. ZnO Nps.

ZnO and CuO NPs have attracted significant attention in recent years for their unique properties and versatile applications. In general, ZnO NPs are characterized by their wide bandgap (about 3.37 eV), higher exciton binding energy, and strong UV absorption, making them suitable for applications in photonics and optoelectronics as UV-blocking agents in sunscreens [47,48]. In addition, their biocompatibility, antibacterial coatings, and drug delivery [49–51]. There are some studies that mainly plant-mediated ZnO NPs synthesized by using different plant counterparts. *Passiflora caerulea* (leaf) is used to synthesize ZnO NPs, using $Zn(O_2CCH_3)_2$ x $2(H_2O)$ precursor, characterized by UV–vis, XRD, FT-IR, SEM, EDAX, and AFM techniques Figure 3. Moreover, we obtained 30–50 nm-sized ZnO NPs from that particular plant leaf. We explored in Table 1 some of the plant-synthesized NPs with their application and characterization. ZnO NPs are essential in environmental remediation, according to recent studies, as they reduce organic contaminants via radiation and other mechanisms [52–54].

Table 1. Key features of CuO nanoparticles.

Plant, Source	Precursor	Conditions	Size	Morphology	Characterization	Application	Key Effects	Ref
Passiflora caerulea, leaf	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	stirred for 1 h	30–50 nm	Spherical	UV–vis, XRD, FT-IR, SEM, EDAX and AFM	Biomedical capability	Showed potential in biomedical applications	[55]
Cassia fistula, leaf	$Zn(NO_3)_3$ x $6H_2O$	heated at 400±10°C	5–15 nm	Irregular	TEM, UV–vis and XRD	Photodegradation, antioxidant, and antibacterial activity	Potential bactericidal activity on *Klebsiella aerogenes, Escherichia coli, Plasmodium desmolyticum*, and *Staphylococcus aureus*, photodegradation against MB, and antioxidant activity for free radical scavenging	[56]
Pongamia pinnata, leaf	$Zn(NO_3)_2$ x $6H_2O$	stirred for 2 h	100 nm	Spherical	XRD, UV–vis, DLS, SEM, TEM, FT-IR, and EDX	Antibacterial activity	ZnO NPs have shown higher antibacterial activity against Gram-positive and Gram-negative bacteria	[57]
Agathosma betulina, leaf	$Zn(NO_3)_2$ x $6H_2O$	Heated at 100°C for 2 hours	15.8 nm	Quasi-spherical	TEM, EDS, XRD, IR, and Raman		Demonstrated a proficient nonlinear current-voltage exponential result	[58]
Azadirachta indica, Hibiscus rosa-sinensis, Murraya koenigii, Moringa oleifera, and *Tamarindus indica*, leaf	$Zn(NO_3)_2$ x $6H_2O$	heated at 120°C for 2 h	27-54 nm	Spherical	FT-IR, XRD, UV–Vis, SEM, TEM and EDX	Antioxidant and antidiabetic activity	*Tamarindus indica* exhibited significant antidiabetic and antioxidant activity as compared to others	[59]
Ocimum Tenuiflorum	$ZnNO_3$	Heated at 70°C until boiling	13.86 nm	hexagonal	XRD, SEM, and FTIR	Lasers, luminescent material, and paints	It can be applied to lasers, luminescent material, paints, and so on	[60]

Plant, Source	Precursor	Conditions	Size	Morphology	Characterization	Application	Key Effects	Ref
Zingiber officinale, root	$ZnCO_3$	Heated at 57°C	23-26 nm	Spherical	FTIR, EDX, SEM and XRD	Antimicrobial activity	showed potential antimicrobial activity against *Klebsiella pneumonia*, *Staphylococcus aureus*, *Candida albicans*, and *Penicillium notatum*, such pathogenic organisms	[61]
Matricaria chamomilla L. (flower), *Olea europaea* (leaf), and *Lycopersicon esculentum M.* (fruit)	ZnO	Stirred for 4 hours	48.2, 65.4, and 61.6 nm, respectively	Cubic structures	UV–Vis,FTIR,XRD,TEM ,SEM and EDS	Antibacterial activity	Antibacterial activity of *Olea europaea* synthesized ZnONPs on *Xanthomonas oryzae pv. Oryza* (Xoo) had a higher inhibition zone of 2.2 cm at 16.0 mg/ml as compared to other plant-extracted nanoparticles, and these biosynthesized nanoparticles were also efficient in bacterial leaf blight diseases for rice amelioration.	[62]
Euphorbia hirta, leaf	$ZnNO_3$	Heated at 60- 90°C	20 -25 nm	Spherical	UV-vis, FT-IR, XRD, and SEM	Antimicrobial Activity and Anti-fungal Activity	The highest antimicrobial activity was shown with the inhibition of *Streptococcus aureus*, with a zone of around 29 mm The highest anti-fungal activity was demonstrated by *Arthrogryposis cuboida* with a zone of inhibition of 29 mm	[63]
Carica papaya, leaf	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	Heated under 60°C for two hours,pH =8	50 nm	Spherical	FESEM, EDS, TEM, PXRD, FT-IR, and UV–Vis	photocatalytic and photovoltaic activity	Exhibited complete dye (MB) degradation within 180 min under UV light scattering	[64]
Tectona grandis (L.), leaf	$ZnNO_3$	Stirred for 10 min	50–150 nm	Spherical	FTIR, UV-Vis, DLS, FT-Raman, FESEM, TEM and PXRD	Anti-bacterial, anti-arthritic, and antioxidant activity	Anticancer activity conducted against osteoblast MC3t3-E1 cancer cells showed a significant reduction in size	[65]
Lippia adoensis, leaf	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	Stirred for 2 h	18.5-26.8 nm	Spherical	XRD, SEM-EDS, TEM, UV-Vis and FTIR	Antibacterial Activity	It is effective against both Gram-positive and Gram-negative bacteria, with 14mm and 12 mm inhibition rates	[66]
Orange fruit, peel	$ZnNO_3$	Stirred for 60 min	10–20 nm	spherical-like	TEM, FTIR, and XRD	Antibacterial activity and bactericidal activity	Strong antibacterial activity against *Escherichia coli (E. coli), Staphylococcus aureus (S. aureus),* and bactericidal activity against *S. aureus*	[67]
Evolvulus alsinoides, leaf	$Zn(O_2CCH_3)_2$	Stirred at 50°C for 10 minutes	100 nm	spherical	FESEM, HRTEM, XRD, UV–Vis and FT-IR	Medicine and industries	It is estimated that the ZnO NPs can be used in industrial applications, medicine, and health care.	[68]
Phyllanthus niruri, leaf	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	Titrated with leaf extract for two h, pH=12	17.2 nm	spherical	XRD,SEM,EDAX,TEM,FT-IR and UV-vis	Photocatalytic and antioxidant activity	The NPs demonstrated significant photocatalytic activity over sunlight and hindered oxidative damage	[69]
Mimosa pudica, leaf, and coffee powder	$Zn(O_2CCH_3)_2$	Stirred overnight	27.14Å and 46.94 Å	nanocrystalline	DTA-TGA, XRD, and DRUV-Vis	Photocatalytic activity	Showed higher photocatalytic activity when DRUV-Vis band gap 2.88eV and 3.10eV for Mimosa pudica, coffee powder, respectively	[70]

Plant, Source	Precursor	Conditions	Size	Morphology	Characterization	Application	Key Effects	Ref
			respectably					
Vitex negundo, leaf	Zn $(NO_3)_2$ x $6H_2O$	stirred for five hours	60 nm	Spherical	XRD, FT- IR, UV-vis, SEM, EDX, and DLS	Antibacterial activity	Significant antibacterial activity against *E. coli* and *S. aureus*	[71]
Trifolium pratense, flower	ZnO	stirred for four hours at 90 ºC	60–70 nm		UV–Vis, XRD, FT-IR, SEM, and EDX	Antibacterial activity	Showed efficacy of ZnO-NPs against clinical and standard strains of *S. aureus, P. aeruginosa, and E. coli*	[72]
thyme plant, leaf	$Zn(NO_3)_2$ x $6H_2O$	Heated and stirred at room temperature for an hour	39.4–51.86 nm	spherical	UV-Vis, FTIR, FEZEM, EDX and XRD		By 450°C calcination temperature, the plant-synthesized ZnO NPs showed higher quality than other temperature-synthesized NPs	[73]
Fumaria officinalis and *Peganum harmala*, leaf			19.55 nm and 25.10 nm	Irregular rods and dispersed spherical	UV–vis FT-IR, XRD, and SEM	Antioxidant and antibacterial activity	To obtain good results as an antioxidant and antibacterial agent, we should use a higher concentration of approximately 400 µg/mL of ZnO NPs	[74]
Cucumis maderaspatanus, leaf	(Zn $(NO3)_2$ x $2H_2O$	heated at 60°C for 2 h, ultrasonication (US)	15–25 nm	spherical	XRD, FTIR, XPS, SEM, and EDAX	Photocatalytic and antibacterial activity	ZnO-US exhibited 100 % suppression within 120 min & 90 % pollutant mineralized, whereas ZnO-60 and ZnO-RT, non-heated, demonstrated results of 80 % and 48 %, respectively	[75]
Tagetes erecta, leaf	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	During four hours heated at 70°C	29 nm	nanorod and nanoflower	XRD, FTIR, SEM, EDX, and UV-Vis		It is a cost-effective and non-toxic nanomaterial that has a wide range of biological and pharmaceutical applications.	[76]
Eucalyptus camaldulensis ,Casuarina cunninghamian and *Anethum graveolens*	$Zn(O_2CCH_3)_2$ x $2(H_2O)$	Stirred at 90°C	10-19 nm	spherical	XRD, UV–vis and TEM	Larvicidal activity and insecticidal agent	ZnO-NPs exhibited the highest insecticidal effect for River oak (*Casuarina cunninghamiana*) as compared to *Eucalyptus camaldulensis* and *Anethum graveolens*	[77]
Ficus benghalensis, leaf	$ZnSO_4$	Stirred at 40°C	60 nm	spherical	EDX, SEM-EDX, XRD, FTIR, and UV–vis	Wastewater treatment	Showed long-term chromium-contaminated wastewater absorption	[78]
Rhus coriaria, fruit	$Zn(C_2H_3O_2)_2$ x $2H_2O$	Heated at 70°C for 2 hours	20.51 ± 3.90 nm	Spherical and hexagonal	UV–Vis, XRD, TEM, EDX and FT-IR	Anticancer activity	Showed promising anti-tumor activity against two breast cancer cells, MCF-7 and MDA-MB-231. IC_{50} values for MCF-7 were 35.04–44.86 µg/mL, and for MDA-MB were 55.54–63.71 µg/ mL	[79]
Citrus limmeta, peel	$Zn(C_2H_3O_2)_2$		16.58 nm	spherical	UV–vis, XRD, FT-IR, HR-SEM and EDX	Antibacterial and antioxidant Activity	The nanopriming results showed complete elimination of soft and brown rot infections in comparison to non-primed potato tuber slices. against plant pathogenic bacteria (*Erwinia carotovora, Ralstonia solanacearum, Clavibacter michiganensis*)	[80]
Eclipta prostrata, leaf	$ZnNO_3$	Heated at room	<100 nm	agglomerated rod	SEM and FT-IR	Antimicrobial activity	Gram+ + and Gram – bacteria, along with fungi,	[81]

Plant, Source	Precursor	Conditions	Size	Morphology	Characterization	Application	Key Effects	Ref
		temperature for 2 hours					demonstrated antimicrobial activity	
Nigella sativa, seed	$Zn(NO_3)_2$	stirred for thirty minutes	43 nm	irregular and large, smooth, uniform, and non-uniform	XRD, SEM, UV–Vis, and FTIR	Anticancer activity	biomedical sciences, particularly in anticancer activity, significant antitumor/anticancer activity towards HepG-2 cells.	[82]
Shilajit, powder	$ZnNO_3$	Heated at 60°C	75-400 nm	Spherical	UV-Vis, FTIR, XRD ,SEM and EDAX	Anticancer activity	Shilajit ZnO NPs have significant cytotoxic effects against cervical cancer cells	[83]
Piper betel, leaf	$ZnNO_3$	Stirred at room temperature for 48 hours	45.8-68 nm	spherical to irregular	UV-vis, XRD, Zeta potential, and SEM	Used as a plant growth parameter	Demonstrated excellent nano-fertilization	[84]
green tea, leaf	zinc acetate dihydrate	stirred for an hour			UV, FTIR, and XRD	anti-dandruff shampoo	Demonstrated potential antifungal activity against *Malassezia furfur*	[85]
Salvadora persica, leaf	$Zn(NO_3)_2$ x $6H_2O$	Heated at 60°C	32-68 nm	hexagonal and rod-shaped	SEM, EDX, FTIR, XRD and UV-Vis	Dye removal activity	Efficient as methyl orange dye removal	[86]
Vernonia amygdalina, leaf	$Zn(C_2H_3O_2)_2$ x $2H_2O$	Reacted for two hours		spherical or elliptical	XRD, FTIR, UV-vis, SEM, and EDX	Antimicrobial activity	The ZnO NPs used as a gentamicin against clinical pathogens	[87]
Strobilanthes hamiltoniana, leaf	Zinc acetate	at 60°C for an hour	10–50 nm	spherical, rod-like, or hexagonal	UV, XRD, FTIR, FESEM, EDX, HR-TEM and SAED	Antibacterial, antioxidant, and anti-cancer activity	Showed promising anti-cancer activity against HepG2 (IC50), antioxidant activity, and antibacterial effectiveness against fungal and bacterial pathogens	[88]
Citrus sinensis, fruit peel	$Zn(NO_3)_2$ x H_2O	Heated a t60°C for 1 hour	31.2 nm,	wurtzite hexagonal	XRD, FTIR, UV-Vis, and EDX	Antibacterial activity	The prepared nanoparticles exhibited bactericidal activity, effectively inhibiting bacterial growth and generating discernible zones of inhibition The antimicrobial potential of the synthesized ZnO NPs was evaluated against two bacterial strains, *Staphylococcus aureus* and *Escherichia coli* Synthesized ZnO NPs can be applied as a potential antibacterial agent	[89]

3.2. CuO NPs.

CuO NPs have demonstrated proficient efficacy in catalyzing and reducing harmful dyes in wastewater treatment and other applications, with a focus on pollution control and related actors [90–92]. Again, encapsulation of the CuO and ZnO NPs into their composite materials has been meticulously designed to improve the mechanical and thermal properties of polymers, and their suitability for advanced synthesized materials is significant [93,94]. Synergistic results have been observed when combining these NPs with other important substances, including metal-organic and graphene structures, which have also caught the attention of current researchers, revealing enhanced sensor performance and photocatalytic activity 95,96]. Despite their potential applications, the toxicity of CuO and ZnO NPs must be thoroughly determined. Research has shown that interactions with biological methods can contribute to cytotoxicity and oxidative stress, prompting deeper studies to identify safer alternatives and techniques to reduce hazardous substances [97,98].

However, CuO NPs demonstrate a smaller bandgap (about 1.2 eV), enabling them to absorb visible light appropriately. This characteristic has manufactured CuO NPs as efficient candidates for photocatalysis and solar energy applications [99]. Moreover, their semiconducting features activate their usage in electronic devices and gas sensors [100,101]. Both CuO and ZnO NPs can be manufactured using various methods, such as sol-gel processes, chemical vapor deposition, and hydrothermal methods, thereby enabling the desired size and morphology, which, in turn, increases their functional properties [102–112].

We have some CuO research in which, for example, Catha edulis (leaf) is used to produce CuO NPs applied as an antibacterial agent with the help of the Cu(NO3) 2 · 3H2O metal precursor, using XRD, SEM-EDS, TEM, UV-Vis, and FTIR techniques. Several plants have been used to manufacture CuO NPs, as shown in Table 2, along with their applications and different characterization methods. In the end, the versatile properties of CuO and ZnO NPs make them indispensable in several fields, from electronic applications and environmental applications to biomedical engineering. Ongoing research into their synthesis, toxicity, and functionalization is important for fully supporting their use in practical applications Figure 4.

Table 2. Key features of CuO nanoparticles.

Plant, sources	**Precursor**	**Conditions**	**Morphology**	**Size**	**Characterization strategies**	**Application**	**Key Effects**	**Ref**
Catha edulis, leaf	$Cu(NO_3)_2$ x $3H_2O$	stirred at 80°C	spherical	Precurs and plant; (1:10, 3:10, and 1: 2), 28.10 nm, 25.30 nm, and 18.20 nm, respectively	XRD, SEM-EDS, TEM, UV-Vis and FTIR	Antibacterial Activity	CuO NPs (1: 2) ratio with the smallest size (18.2 nm) demonstrated the best antibacterial activity	[113]
Allium Sativum	$Cu(NO_3)_2$	Heated at 70°C for 2-3 hours	spherical, oval-shaped	20-50 nm	FTIR, XRD, UV-Vis, SEM, and HRTEM	Antimicrobial, antioxidant, and anti-larvicidal activity	Anti-larvicidal activity, anti-inflammatory activity, antimicrobial activity against *Anopheles subpictus*, egg albumin, bacteria, and fungi, respectively	[114]
Calotropis gigantea, leaf	$Cu(NO_3)_2$	400°C for 2 hours	spherical	20-30 nm	FESEM, EDX, TEM, XRD, and FTIR	solar cells	CuO NPs-based counter electrode exhibited potential electrocatalytic activity without any harmful chemicals	[115]
Plectranthus amboinicus, leaf	$Cu(NO_3)_2$	Stirred for 3-4 hours at 70°C	spherical, circular-shaped	5–30 nm	XRD, FTIR, UV-Vis, DLS, FESEM, EDAX, and HRTEM	Antimicrobial activity, Anti-diabetic activity, Anti-larvicidal activity, Antioxidant activity, and Anti-inflammatory analysis	The antimicrobial acts on bacteria and fungi. Antioxidant activity: free-radical scavenging. The anti-inflammatory activity of the protein as well as denaturation in egg albumin. The anti-diabetic activity on α-Amylase. The anti-larvicidal activity on mosquito larvae.	[116]
Catha edulis, leaf	$CuSO_4$ x $5H_2O$	pH = 11		1-8 nm	FT-IR and UV-Vis	Antibacterial Activity	Exhibited efficient antimicrobial activity against two human pathogens, *Salmonella typhimurium* and *Escherichia coli*	[117]
Lantana camara, flower	$Cu(CH_3COO)_2$	stirred at 65 °C	rod-shaped, spherical	13-28 nm	SEM, HRTEM, TEM, SAED,and XRD	catalytic activity	Significant yield catalyst and reusable up to the fifth generation.	[118]
Jasminium sambac, leaf	$CuSO_4$ x $5H_2O$	dried at 60°C for 2 hours	irregular	13.4 nm	UV–Vis, SEM, XRD, FTIR, and EDX	photocatalytic activity	Got 97% MB (Methylene Blue) dye degradation within 210 minutes, powerful	[119]

Plant, sources	Precursor	Conditions	Morphology	Size	Characterization strategies	Application	Key Effects	Ref
							photocatalytic activity in wastewater remediation	
Aloe vera, leaf	copper nitrate	stirred at 100-120°C	versatile and spherical	20 nm	SEM-EDS, FTIR, UV–Vis, XRD and TEM	Antibacterial activity	Showed proficient antibacterial activity against three bacterial fish pathogens (*Pseudomonas fluorescens and Aeromonas hydrophila, Flavobacterium branchiophilum)*	[120]
Moringa Oleifera, leaf	$CuSO_4$ x $5H_2O$	dried at 100°C for 1 h	Nanorods	25.93 nm	XRD, UV-Vis, EDS, EIS, SEM, and GCD	Supercapacitor and energy storage	Significant applications as a supercapacitor and other energy storage	[121]
Spinacia oleracea, leaf	$CuSO_4$	stirred at 80°C	oval, spherical, hexagonal, and cubical	20-80 nm	UV-Vis, FT-IR, and X-Ray diffraction	Bactericidal, antifungal, and larvicidal activity	Showed excellent bactericidal activity to *Staphylococcus aureus, Escherichia Coli, Proteus, Klebsiella*, and significant antifungal activity to *A. flavus*, *Rhizopus*, and *A. fumigant* and larvicidal activity to *Culex. Quinquefasciatus*	[122]
Sesbania grandiflora, leaf	$CuSO_4$	stirred at 60°C	needle-shaped	33 nm	UV-Vis ,UV-Vis DRS, FTIR, XRD, SEM, and EDAX	Anti-diabetic, Cytotoxic, Anti-Microbial, and Anti-Inflammatory	Demonstrated significant antidiabetic, antioxidant, protein degradation-inhibiting, and anti-microbial characteristics	[123]
Punica granatum, peel	$Cu(CH_3\text{-}COO)_2$ x H_2O	pH 10 at 60 C	well-dispersed and spherical	35.80 nm	XRD, FTIR, SEM	Antibacterial activity	Demonstrated bacterial strain to *Escherichia coli*	[124]
Eucalyptus globulus, leaf	anhydrous copper sulfate	Vibrated room temperature for 2 hours	Spherical,	88 nm	FTIR, XRD, SEM, DLS	dye removal	Applied to banish methyl orange dye from aqueous solutions	[125]
Cedrus deodara, leaf	copper sulfate pentahydrate	150 rpm for two hours	Spherical	20 nm	SEM, XRD, UV–Vis, TEM and FTIR	Antibacterial activity	The CuO nanoparticles were tested to inhibit the growth of human pathogenic strains with the help of the disc diffusion method against E. coli and S. aureus. It is noted that the formed CuO nanoparticles showed efficient antibacterial activity, especially against E. coli, with a maximum inhibition zone of 29 mm	[126]
Ephedra Alata, aerial parts' powder	$CuSO_4$ x $5H_2O$	Boiled at 90°C	octahedral crystal clusters and spherical	15.21 nm	XRD, UV-Vis, FTIR and FESEM-EDX	Antifungal, antibacterial, and photocatalytic activity	Bio-synthesized CuO-NPs exhibited higher Antifungal, antibacterial, and photocatalytic activity than chemically synthesized CuO-NPs	[127]
Ixoro coccinea, leaf	$CuSO_4$ x $5H_2O$	kept the mixture at room temperature overnight	Spherical	80–110 nm	FTIR, SEM, TEM, and UV-visible spectrophotometer		Cost-effective and environmentally friendly	[128]
Gloriosa superba L, leaf	cupric nitrate	400 ± 10°C	Spherical	5–10 nm	XRD, SEM, TEM, and UV–vis	Antibacterial activity	Exhibited significant antibacterial activity against both gram-positive (*Staphylococcus aureus*) and gram-negative (*Klebsiella aerogenes, Pseudomonas desmolyticum, and Escherichia coli*) bacteria, respectively	[129]

Plant, sources	Precursor	Conditions	Morphology	Size	Characterization strategies	Application	Key Effects	Ref
Abelmoschus esculentus, fruit	$Cu(NO_3)_2$ x $3H_2O$	stirred the mixture for 30 min at 25°C	spherical	20 nm	TGA/DTA, UV–Vis, DRS, XRD, FTIR, BET, TEM, FESEM/EDX, and PSA	Cytotoxic and photocatalytic activity	Showed great performance in damaging cancer cells and is an effective photocatalyst for removing pollution	[130]

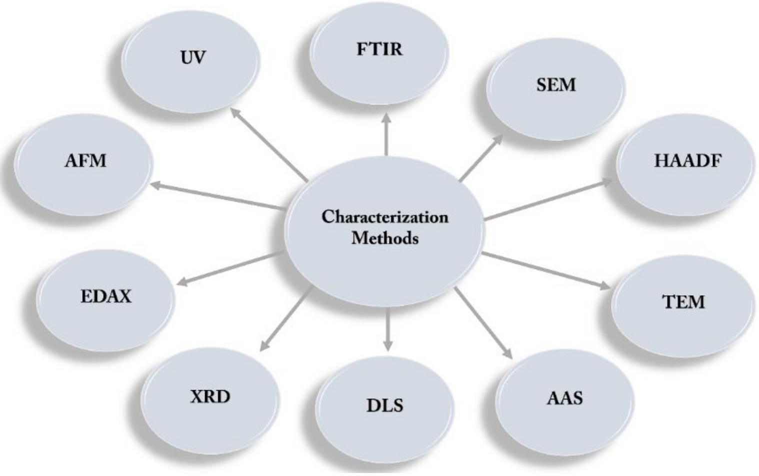

Figure 3. Various characterization methods.

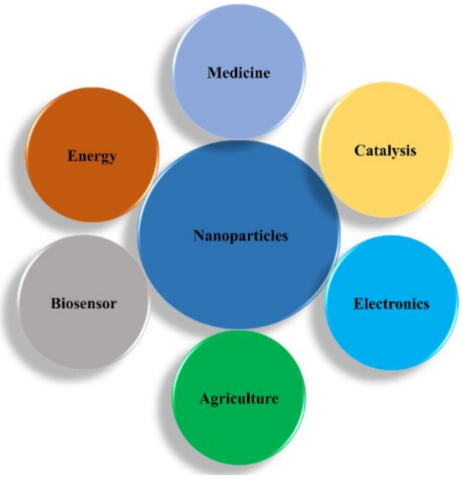

Figure 4. Applications of Nanoparticles in versatile fields.

4. Future Directions and Applications

With the continuous advancement of nanotechnology, the green synthesis of ZnO and CuO NPs promotes an exciting prospect for future research and applications. Numerous key directions have been pursued to enhance the impact of these biogenic NPs across various fields. A deep realization of the mechanisms underscoring the green synthesis of CuO and ZnO NPs is important for optimizing production methods. Future studies should focus on describing the specific roles of various phytochemicals involved in the reduction and stabilization of metal ions. Visualizing how entities, including pH, temperature, and extract concentration, affect the size and morphology of nanoparticles can lead to standardized protocols that enhance the reproducibility and scalability of synthesized nanoparticles. Implementing advanced characterization strategies, such as HRTEM and dynamic light scattering DLS, will yield a more transparent analysis of the NPs' characteristics, enabling numerous applications [131–134].

While many plant species have demonstrated efficiency in synthesizing CuO and ZnO nanoparticles, a broader study of biodiversity could reveal additional effective raw materials.

Scrutinizing useless or novel plant extracts, such as medicinal herbs and agricultural waste ingredients, can lead to a sustainable method of repurposing biomass [135,136]. Moreover, research should evaluate the suitability of integrating these extracts into industrial systems, supporting a circular economy that reduces waste by enabling cost-effective NP synthesis [137,138].

The biomedical applications of CuO and ZnO NPs are particularly promising, as they are environmentally friendly and offer dormant antimicrobial and therapeutic properties. Future research could focus on developing NP-based drug delivery systems that enhance the bioavailability and potential of several therapeutics, particularly for treating infectious diseases and cancer [139–142]. Modification of NPs with specific targeting ligands or the use of biocompatible polymers can improve their selectivity and reduce potential side effects. In addition, a deeper study of the interactions between these NPs and biological systems will promote insights into their behavior in vivo, clearing the way for clinical applications and so on [143–146].

The role of CuO and ZnO NPs in environmental remediation represents another potential area for future research. Their photocatalytic properties make them ideal candidates for breaking down pollutants in water [147]. Investigating the potential of these nanoparticles to reduce pollutants, such as pharmaceuticals and heavy metals, will improve our understanding of their environmental effects [148–150].

Moreover, predicting their incorporation into filtration methods or catalytic converters could ameliorate their empirical utility in addressing many pollution challenges.

Encapsulation of CuO and ZnO nanoparticles into smart materials can improve various sectors, including energy, electronics, and textiles. Their unique features offer the development of flexible electronics, sensors, and antimicrobial coatings [151–156]. Future research should assess the applicability of these NPs with advanced technologies, including 3D printing and nanocomposite materials, to develop multifunctional strategies. In addition, their potential uses in energy applications, for example, solar cells and batteries, could open new doors for sustainable energy [157–159].

As the applications of plant-synthesized nanoparticles expand, establishing standardized protocols and regulatory frameworks is important. Future research should examine the need for safety evaluations and environmental impact analyses to ensure the appropriate use of CuO and ZnO NPs. The development of guidelines for their characterization, synthesis, and application will encourage greater acceptance and simplify their integration into many industries. Collaboration among many researchers, industry stakeholders, and regulatory bodies will be essential to address these challenges [160].

The complex characteristics of NPs synthesis and application require multifaceted research practices. Cooperation among chemists, environmental scientists, biologists, and engineers can lead to groundbreaking research and widespread studies that express multiple features of NPs research. Collaborating with industry can also help translate research gaps into field applications by promoting technological advancements and market value [161–164].

The future of plant-synthesized CuO and ZnO NPs is bright, with amorous approaches to explanation that prioritize increasing their utility and impact across many fields. By emphasizing mechanistic realization, expressing raw material resources, and focusing on new applications in drug delivery, smart materials, and environmental remediation, researchers can activate the full potential of these green nanomaterials. The basement of innovative frameworks and multifaceted collaboration will, overall, make it easier to responsibly develop and apply

CuO and ZnO NPs by contributing to sustainable solutions for combating global challenges. As the body of research on green synthesis continues to grow, these contributions are expected to improve citation rates and knowledge within the scientific community by positioning the work at the forefront of nanotechnology advancements.

5. Conclusion

Nanotechnology has caught the eye and brought revolutionary changes across various fields, such as medicine and agriculture. It is also a major concern that the methods of synthesis for these nanoparticles are vital to examine due to environmental contamination. Chemical synthesis methods are environmentally harmful and pose greater risks to human health. That is why this study demonstrated various ways to synthesize CuO and ZnO NPs from plant sources and their characterization methods, thereby securing the environment from various contaminants and reducing financial expenses through cost-effective green synthesis methods. Because nanotechnology is most effective due to its unique properties and sizes, it performs better than other chemically synthesized materials. Moreover, it is easier to manufacture NPs from natural resources than from chemically synthesized materials, particularly from various plant sources. If we use plant-based synthesis, called green synthesis, the methods here are cost-effective and environmentally supportive, and won't damage the environment in terms of global temperature. That is why this study will help readers gain comprehensive knowledge of plant-mediated CuO and ZnO NPs, with their effective characterization and applications. However, there are still some challenges in synthesizing NPs, including the need for proper instruments and reduced production. Future studies should focus on reducing the amount of metal precursor and on elucidating the exact mechanism.

Author Contributions

Conceptualization, J.S.; methodology, J.S.; software, J.S.; validation, J.S.; formal analysis, J.S.; investigation, J.S.; resources, J.S.; data curation, J.S.; writing—original draft preparation, J.S.; writing—review and editing, J.S.; visualization, J.S.; supervision, J.S.; project administration, J.S.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study

Funding

Not applicable.

Acknowledgments

Not applicable.

Conflict of interest

Not applicable.

References

1. Lawrynowicz, A.; Palo, E.; Nizamov, R.; Miettunen, K. Self-cleaning and UV-blocking cotton – Fabricating effective ZnO structures for photocatalysis. *J. Photochem. Photobiol. A-Chem.* **2024**, *450*, 115420, https://doi.org/10.1016/J.JPHOTOCHEM.2023.115420.
2. Uribe-López, M.C.; Hidalgo-López, M.C.; López-González, R.; Frías-Márquez, D.M.; Núñez-Nogueira, G.; Hernández-Castillo, D.; Alvarez-Lemus, M.A. Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties. *J. Photochem. Photobiol. A-Chem.* **2021**, *404*, 112866, https://doi.org/10.1016/J.JPHOTOCHEM.2020.112866.
3. Omar, F.M.; Aziz, H.A.; Stoll, S. Stability of ZnO Nanoparticles in Solution. Influence of pH, Dissolution, Aggregation, and Disaggregation Effects. *J. Colloid Sci. Biotechnol.* **2014**, *3*, 1-10.
4. Kumar, P.; Walia, Y.K. Synthesis and Structural properties of Zinc Oxide Nano Particles (ZnO NPs): A Review. *Asian J. Adv. Basic Sci.* **2014**, *2*, 39-49.
5. Alberti, S.; Basciu, I.; Vocciante, M.; Ferretti, M. Experimental and Physico-Chemical Comparison of ZnO Nanoparticles' Activity for Photocatalytic Applications in Wastewater Treatment. *Catalysts* **2021**, *11*, 678, https://doi.org/10.3390/catal11060678.
6. Halfadji, A.; Naous, M.; Rajendrachari, S.; Ceylan, Y.; Ceylan, K.B.; Shekar, P.V.R. Effective investigation of electro-catalytic, photocatalytic, and antimicrobial properties of porous CuO nanoparticles green synthesized using leaves of *Cupressocyparis leylandii*. *J. Mol. Struct.* **2024**, *1301*, 137318, https://doi.org/10.1016/j.molstruc.2023.137318.
7. Ul-Hamid, A.; Dafalla, H.; Hakeem, A.S.; Haider, A.; Ikram, M. In-Vitro Catalytic and Antibacterial Potential of Green Synthesized CuO Nanoparticles against Prevalent Multiple Drug Resistant Bovine Mastitogen *Staphylococcus aureus*. *Int. J. Mol. Sci.* **2022**, *23*, 2335, https://doi.org/10.3390/ijms23042335.
8. Khorsandi, K.; Hosseinzadeh, R.; Sadat Esfahani, H.; Keyvani-Ghamsari, S.; Ur Rahman, S. Nanomaterials as drug delivery systems with antibacterial properties: current trends and future priorities. *Expert Rev. Anti. Infect. Ther.* **2021**, *19*, 1299-1323, https://doi.org/10.1080/14787210.2021.1908125.
9. Kim, M.-s.; Choi, K.-h.; Kim, Y.-H.; Yi, J.-H. Risk Assessment for Health and Environmental Hazards of Nanomaterials. *Clean Technol.* **2007**, *13*, 161-172.
10. Satterthwaite, D. The implications of population growth and urbanization for climate change. *Environ. Urban.* **2009**, *21*, 545-567, https://doi.org/10.1177/0956247809344361.
11. Hussain, I.; Singh, N.B.; Singh, A.; Singh, H.; Singh, S.C. Green synthesis of nanoparticles and its potential application. *Biotechnol. Lett.* **2016**, *38*, 545-560, https://doi.org/10.1007/S10529-015-2026-7.
12. El-Seedi, H.R.; El-Shabasy, R.M.; Khalifa, S.A.M.; Saeed, A.; Shah, A.; Shah, R.; Iftikhar, F.J.; Abdel-Daim, M.M.; Omri, A.; Hajrahand, N.H.; Sabir, J.S.M.; Zou, X.; Halabi, M.F.; Sarhan, W.; Guo, W. Metal nanoparticles fabricated by green chemistry using natural extracts: biosynthesis, mechanisms, and applications. *RSC Adv.* **2019**, *9*, 24539-24559, https://doi.org/10.1039/C9RA02225B.
13. Chan, Y.B.; Aminuzzaman, M.; Win, Y.F.; Djearamane, S.; Wong, L.S.; Guha, S.K.; Almohammadi, H.; Akhtaruzzaman, M.; Tey, L.-H. *Garcinia mangostana* L. Leaf-Extract-Assisted Green Synthesis of CuO, ZnO and CuO-ZnO Nanomaterials for the Photocatalytic Degradation of Palm Oil Mill Effluent (POME). *Catalysts* **2024**, *14*, 486, https://doi.org/10.3390/catal14080486.
14. Jadoun, S.; Arif, R.; Jangid, N.K.; Meena, R.K. Green synthesis of nanoparticles using plant extracts: a review. *Environ. Chem. Lett.* **2021**, *19*, 355-374, https://doi.org/10.1007/s10311-020-01074-x.
15. Gough, C.R.; Rivera-Galletti, A.; Cowan, D.A.; Salas-de la Cruz, D.; Hu, X. Protein and Polysaccharide-Based Fiber Materials Generated from Ionic Liquids: A Review. *Molecules* **2020**, *25*, 3362, https://doi.org/10.3390/molecules25153362.

16. Li, J.; Jiang, Z.; Wu, H.; Liang, Y.; Zhang, Y.; Liu, J. Enzyme–polysaccharide interaction and its influence on enzyme activity and stability. *Carbohydr. Polym.* **2010**, *82*, 160-166, https://doi.org/10.1016/j.carbpol.2010.04.045.
17. Faisal, S.; Jan, H.; Shah, S.A.; Shah, S.; Khan, A.; Akbar, M.T.; Rizwan, M.; Jan, F.; Wajidullah; Akhtar, N.; Khattak, A.; Syed, S. Green Synthesis of Zinc Oxide (ZnO) Nanoparticles Using Aqueous Fruit Extracts of *Myristica fragrans*: Their Characterizations and Biological and Environmental Applications. *ACS Omega* **2021**, *6*, 9709-9722, https://doi.org/10.1021/acsomega.1c00310.
18. Dey, S.; Mohanty, D.l.; Divya, N.; Bakshi, V.; Mohanty, A.; Rath, D.; Das, S.; Mondal, A.; Roy, S.; Sabui, R. A critical review on zinc oxide nanoparticles: Synthesis, properties and biomedical applications. *Intell. Pharm.* **2025**, *3*, 53-70, https://doi.org/10.1016/J.IPHA.2024.08.004.
19. Adeyemi, J.O.; Oriola, A.O.; Onwudiwe, D.C.; Oyedeji, A.O. Plant Extracts Mediated Metal-Based Nanoparticles: Synthesis and Biological Applications. *Biomolecules* **2022**, *12*, 627, https://doi.org/10.3390/BIOM12050627.
20. Sidhu, A.K.; Verma, N.; Kaushal, P. Role of Biogenic Capping Agents in the Synthesis of Metallic Nanoparticles and Evaluation of Their Therapeutic Potential. *Front. Nanotechnol.* **2022**, *3*, 801620, https://doi.org/10.3389/FNANO.2021.801620.
21. Das, S.; Bhardwaj, A.; Pandey, L.M. Functionalized Biogenic Nanoparticles for Use in Emerging Biomedical Applications: A Review. *Curr. Nanomater.* **2021**, *6*, 119-139, https://doi.org/10.2174/2468187310999201222112144.
22. Darroudi, M.; Yazdi, M.E.T.; Amiri, M.S. Plant-mediated biosynthesis of nanoparticles. In 21st Century Nanoscience–A Handbook, 1st Edition; Sattler, K.D., Ed.; CRC Press: Boca Raton, **2020**; Volume 7, pp. 1-1, https://doi.org/10.1201/9780429351525-1.
23. Küünal, S.; Rauwel, P.; Rauwel, E. Chapter 14 - Plant extract mediated synthesis of nanoparticles. In Emerging Applications of Nanoparticles and Architecture Nanostructures, Barhoum, A., Makhlouf, A.S.H., Eds.; Elsevier: **2018**; pp. 411-446, https://doi.org/10.1016/B978-0-323-51254-1.00014-2.
24. Raj, S.; Chand Mali, S.; Trivedi, R. Green synthesis and characterization of silver nanoparticles using *Enicostemma axillare* (Lam.) leaf extract. *Biochem. Biophys. Res. Commun.* **2018**, *503*, 2814-2819, https://doi.org/10.1016/j.bbrc.2018.08.045.
25. Banala, R.R.; Nagati, V.B.; Karnati, P.R. Green synthesis and characterization of *Carica papaya* leaf extract coated silver nanoparticles through X-ray diffraction, electron microscopy and evaluation of bactericidal properties. *Saudi J. Biol. Sci.* **2015**, *22*, 637-644, https://doi.org/10.1016/j.sjbs.2015.01.007.
26. Salatin, S.; Maleki Dizaj, S.; Yari Khosroushahi, A. Effect of the surface modification, size, and shape on cellular uptake of nanoparticles. *Cell Biol. Int.* **2015**, *39*, 881-890, https://doi.org/10.1002/CBIN.10459.
27. Barnard, A.S.; Zapol, P. A model for the phase stability of arbitrary nanoparticles as a function of size and shape. *J. Chem. Phys.* **2004**, *121*, 4276-4283, https://doi.org/10.1063/1.1775770.
28. An, K.; Somorjai, G.A. Size and Shape Control of Metal Nanoparticles for Reaction Selectivity in Catalysis. *ChemCatChem* **2012**, *4*, 1512-1524, https://doi.org/10.1002/CCTC.201200229.
29. Bhakya, S.; Muthukrishnan, S.; Sukumaran, M.; Muthukumar, M. Biogenic synthesis of silver nanoparticles and their antioxidant and antibacterial activity. *Appl. Nanosci.* **2016**, *6*, 755-766, https://doi.org/10.1007/S13204-015-0473-Z.
30. Gebre, S.H.; Sendeku, M.G. New frontiers in the biosynthesis of metal oxide nanoparticles and their environmental applications: an overview. *SN Appl. Sci.* **2019**, *1*, 928, https://doi.org/10.1007/s42452-019-0931-4.
31. Zafar, M.; Iqbal, T.; Afsheen, S.; Iqbal, A.; Shoukat, A. An overview of green synthesis of zinc oxide nanoparticle by using various natural entities. *Inorg. Nano-metal Chem.* **2024**, *54*, 1067-1084, https://doi.org/10.1080/24701556.2023.2165681.
32. El Shafey, A.M. Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review. *Green Process. Synth.* **2020**, *9*, 304-339.
33. Bahrulolum, H.; Nooraei, S.; Javanshir, N.; Tarrahimofrad, H.; Mirbagheri, V.S.; Easton, A.J.; Ahmadian, G. Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *J. Nanobiotechnol.* **2021**, *19*, 86, https://doi.org/10.1186/s12951-021-00834-3.
34. Khan, M.R.; Adam, V.; Rizvi, T.F.; Zhang, B.; Ahamad, F.; Jośko, I.; Zhu, Y.; Yang, M.; Mao, C. Nanoparticle–Plant Interactions: Two-Way Traffic. *Small* **2019**, *15*, 1901794, https://doi.org/10.1002/smll.201901794.

35. Vijayaraghavan, K.; Ashokkumar, T. Plant-mediated biosynthesis of metallic nanoparticles: A review of literature, factors affecting synthesis, characterization techniques and applications. *J. Environ. Chem. Eng.* **2017**, *5*, 4866-4883, https://doi.org/10.1016/j.jece.2017.09.026.
36. Bhati, M. Biogenic synthesis of metallic nanoparticles: Principles and applications. *Mater. Today Proc.* **2023**, *81*, 882-887, https://doi.org/10.1016/j.matpr.2021.04.272.
37. Hernández-Díaz, J.A.; Garza-García, J.J.O.; Zamudio-Ojeda, A.; León-Morales, J.M.; López-Velázquez, J.C.; García-Morales, S. Plant-mediated synthesis of nanoparticles and their antimicrobial activity against phytopathogens. *J. Sci. Food Agric.* **2021**, *101*, 1270-1287, https://doi.org/10.1002/jsfa.10767.
38. Flieger, J.; Flieger, W.; Baj, J.; Maciejewski, R. Antioxidants: Classification, Natural Sources, Activity/Capacity Measurements, and Usefulness for the Synthesis of Nanoparticles. *Materials* **2021**, *14*, 4135, https://doi.org/10.3390/ma14154135.
39. Miu, B.A.; Dinischiotu, A. New Green Approaches in Nanoparticles Synthesis: An Overview. *Molecules* **2022**, *27*, 6472, https://doi.org/10.3390/molecules27196472.
40. Yashni, G.; Al-Gheethi, A.A.; Mohamed, R.M.S.R.; Amir Hashim, M.K. Green synthesis of ZnO nanoparticles by Coriandrum sativum leaf extract: structural and optical properties. *Desalination Water Treat.* **2019**, *167*, 245-257, https://doi.org/10.5004/dwt.2019.24584.
41. Kumar, P.P.N.V.; Shameem, U.; Kollu, P.; Kalyani, R.L.; Pammi, S.V.N. Green Synthesis of Copper Oxide Nanoparticles Using *Aloe vera* Leaf Extract and Its Antibacterial Activity Against Fish Bacterial Pathogens. *BioNanoScience* **2015**, *5*, 135-139, https://doi.org/10.1007/S12668-015-0171-Z.
42. Sharma, S.; Kumar, K. Aloe-vera leaf extract as a green agent for the synthesis of CuO nanoparticles inactivating bacterial pathogens and dye. *J. Dispers. Sci. Technol.* **2021**, *42*, 1950-1962, https://doi.org/10.1080/01932691.2020.1791719.
43. Senthilkumar, P.; Yaswant, G.; Kavitha, S.; Chandramohan, E.; Kowsalya, G.; Vijay, R.; Sudhagar, B.; Kumar, D.S.R.S. Preparation and characterization of hybrid chitosan-silver nanoparticles (Chi-Ag NPs); A potential antibacterial agent. *Int. J. Biol. Macromol.* **2019**, *141*, 290-298, https://doi.org/10.1016/j.ijbiomac.2019.08.234.
44. Sengani, M.; Grumezescu, A.M.; Rajeswari, V.D. Recent trends and methodologies in gold nanoparticle synthesis – A prospective review on drug delivery aspect. *OpenNano* **2017**, *2*, 37-46, https://doi.org/10.1016/j.onano.2017.07.001.
45. Ganeshkumar, M.; Sathishkumar, M.; Ponrasu, T.; Dinesh, M.G.; Suguna, L. Spontaneous ultra fast synthesis of gold nanoparticles using *Punica granatum* for cancer targeted drug delivery. *Colloids Surf. B: Biointerfaces* **2013**, *106*, 208-216, https://doi.org/10.1016/j.colsurfb.2013.01.035.
46. Yallappa, S.; Manjanna, J.; Dhananjaya, B.L.; Vishwanatha, U.; Ravishankar, B.; Gururaj, H. Phytosynthesis of gold nanoparticles using *Mappia foetida* leaves extract and their conjugation with folic acid for delivery of doxorubicin to cancer cells. *Mater. Sci.: Mater. Med.* **2015**, *26*, 235, https://doi.org/10.1007/s10856-015-5567-3.
47. Aldeen, T.S.; Ahmed Mohamed, H.E.; Maaza, M. ZnO nanoparticles prepared via a green synthesis approach: Physical properties, photocatalytic and antibacterial activity. *J. Phys. Chem. Solids* **2022**, *160*, 110313, https://doi.org/10.1016/j.jpcs.2021.110313.
48. Mahdi Ismail, S.M.; Ahmed, S.M.; Abdulrahman, A.F.; AlMessiere, M.A. Characterization of green synthesized of ZnO nanoparticles by using pinus brutia leaves extracts. *J. Mol. Struct.* **2023**, *1280*, 135063, https://doi.org/10.1016/j.molstruc.2023.135063.
49. Turlybekuly, A.; Pogrebnjak, A.D.; Sukhodub, L.F.; Sukhodub, L.B.; Kistaubayeva, A.S.; Savitskaya, I.S.; Shokatayeva, D.H.; Bondar, O.V.; Shaimardanov, Z.K.; Plotnikov, S.V.; Shaimardanova, B.H.; Digel, I. Synthesis, characterization, *in vitro* biocompatibility and antibacterial properties study of nanocomposite materials based on hydroxyapatite-biphasic ZnO micro- and nanoparticles embedded in Alginate matrix. *Mater. Sci. Eng., C* **2019**, *104*, 109965, https://doi.org/10.1016/j.msec.2019.109965.
50. Tavakoli, S.; Kharaziha, M.; Nemati, S. Polydopamine coated ZnO rod-shaped nanoparticles with noticeable biocompatibility, hemostatic and antibacterial activity. *Nano-Struct. Nano-Objects* **2021**, *25*, 100639, https://doi.org/10.1016/j.nanoso.2020.100639.
51. Mahalakshmi, S.; Hema, N.; Vijaya, P.P. In Vitro Biocompatibility and Antimicrobial activities of Zinc Oxide Nanoparticles (ZnO NPs) Prepared by Chemical and Green Synthetic Route— A Comparative Study. *BioNanoScience* **2020**, *10*, 112-121, https://doi.org/10.1007/s12668-019-00698-w.

52. Ali, A.; Phull, A.-R.; Zia, M. Elemental zinc to zinc nanoparticles: is ZnO NPs crucial for life? Synthesis, toxicological, and environmental concerns. *Nanotechnol. Rev.* **2018**, *7*, 413–441, https://doi.org/10.1515/NTREV-2018-0067.
53. Zelekew, O.A.; Haitosa, H.H.; Chen, X.; Wu, Y.-N. Recent progress on plant extract-mediated biosynthesis of ZnO-based nanocatalysts for environmental remediation: Challenges and future outlooks. *Adv. Colloid Interface Sci.* **2023**, *317*, 102931, https://doi.org/10.1016/j.cis.2023.102931.
54. Singh, J.; Dutta, T.; Kim, K.-H.; Rawat, M.; Samddar, P.; Kumar, P. ‘Green’ synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *J. Nanobiotechnol.* **2018**, *16*, 84, https://doi.org/10.1186/S12951-018-0408-4.
55. Santhoshkumar, J.; Kumar, S.V.; Rajeshkumar, S. Synthesis of zinc oxide nanoparticles using plant leaf extract against urinary tract infection pathogen. *Resour. Effic. Technol.* **2017**, *3*, 459-465, https://doi.org/10.1016/j.reffit.2017.05.001.
56. Suresh, D.; Nethravathi, P.C.; Udayabhanu; Rajanaika, H.; Nagabhushana, H.; Sharma, S.C. Green synthesis of multifunctional zinc oxide (ZnO) nanoparticles using *Cassia fistula* plant extract and their photodegradative, antioxidant and antibacterial activities. *Mater. Sci. Semicond. Process* **2015**, *31*, 446-454, https://doi.org/10.1016/j.mssp.2014.12.023.
57. Sundrarajan, M.; Ambika, S.; Bharathi, K. Plant-extract mediated synthesis of ZnO nanoparticles using *Pongamia pinnata* and their activity against pathogenic bacteria. *Adv. Powder Technol.* **2015**, *26*, 1294-1299, https://doi.org/10.1016/j.apt.2015.07.001.
58. Thema, F.T.; Manikandan, E.; Dhlamini, M.S.; Maaza, M. Green synthesis of ZnO nanoparticles via *Agathosma betulina* natural extract. *Mater. Lett.* **2015**, *161*, 124-127, https://doi.org/10.1016/j.matlet.2015.08.052.
59. Rehana, D.; Mahendiran, D.; Kumar, R.S.; Rahiman, A.K. In vitro antioxidant and antidiabetic activities of zinc oxide nanoparticles synthesized using different plant extracts. *Bioprocess Biosyst. Eng.* **2017**, *40*, 943-957, https://doi.org/10.1007/s00449-017-1758-2.
60. Raut, S.; Thorat, P.V.; Thakre, R. Green Synthesis of Zinc Oxide (ZnO) Nanoparticles Using Ocimum Tenuiflorum Leaves. *Int. J. Sci. Res.* **2013**, *4*, 1225-1228.
61. Janaki, A.C.; Sailatha, E.; Gunasekaran, S. Synthesis, characteristics and antimicrobial activity of ZnO nanoparticles. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2015**, *144*, 17-22, https://doi.org/10.1016/J.SAA.2015.02.041.
62. Ogunyemi, S.O.; Abdallah, Y.; Zhang, M.; Fouad, H.; Hong, X.; Ibrahim, E.; Masum, M.M.I.; Hossain, A.; Mo, J.; Li, B. Green synthesis of zinc oxide nanoparticles using different plant extracts and their antibacterial activity against *Xanthomonas oryzae* pv. oryzae. *Artif. Cells Nanomed. Biotechnol.* **2019**, *47*, 341-352, https://doi.org/10.1080/21691401.2018.1557671.
63. Ahmad, W.; Kalra, D. Green synthesis, characterization and anti microbial activities of ZnO nanoparticles using *Euphorbia hirta* leaf extract. *J. King Saud Univ. Sci.* **2020**, *32*, 2358–2364, https://doi.org/10.1016/J.JKSUS.2020.03.014.
64. Rathnasamy, R.; Thangasamy, P.; Thangamuthu, R.; Sampath, S.; Alagan, V. Green synthesis of ZnO nanoparticles using *Carica papaya* leaf extracts for photocatalytic and photovoltaic applications. *J. Mater. Sci.: Mater. Electron.* **2017**, *28*, 10374-10381, https://doi.org/10.1007/S10854-017-6807-8.
65. Senthilkumar, N.; Nandhakumar, E.; Priya, P.; Soni, D.; Vimalan, M.; Vetha Potheher, I. Synthesis of ZnO nanoparticles using leaf extract of *Tectona grandis* (L.) and their anti-bacterial, anti-arthritic, anti-oxidant and *in vitro* cytotoxicity activities. *New J. Chem.* **2017**, *41*, 10347-10356, https://doi.org/10.1039/c7nj02664a.
66. Demissie, M.G.; Sabir, F.K.; Edossa, G.D.; Gonfa, B.A. Synthesis of Zinc Oxide Nanoparticles Using Leaf Extract of *Lippia adoensis* (Koseret) and Evaluation of Its Antibacterial Activity. *J. Chem.* **2020**, *2020*, 7459042, https://doi.org/10.1155/2020/7459042.
67. Doan Thi, T.U.; Nguyen, T.T.; Thi, Y.D.; Ta Thi, K.H.; Phan, B.T.; Pham, K.N. Green synthesis of ZnO nanoparticles using orange fruit peel extract for antibacterial activities. *RSC Adv.* **2020**, *10*, 23899-23907, https://doi.org/10.1039/D0RA04926C.
68. Yadav, A.; Jangid, N.K.; Khan, A.U. Biogenic synthesis of ZnO nanoparticles from Evolvulus alsinoides plant extract. *J.Umm Al-Qura Univ. Appl. Sci.* **2024**, *10*, 51-57, https://doi.org/10.1007/s43994-023-00076-z.

69. Ramesh, P.; Rajendran, A.; Ashokkumar, M. Biosynthesis of zinc oxide nanoparticles from *Phyllanthus Niruri* plant extract for photocatalytic and antioxidant activities. *Int. J. Environ. Anal. Chem.* **2024**, *104*, 1561-1572, https://doi.org/10.1080/03067319.2022.2041004.
70. Fatimah, I.; Pradita, R.Y.; Nurfalinda, A. Plant Extract Mediated of ZnO Nanoparticles by Using Ethanol Extract of Mimosa Pudica Leaves and Coffee Powder. *Procedia Eng.* **2016**, *148*, 43-48, https://doi.org/10.1016/j.proeng.2016.06.483.
71. Ambika, S.; Sundrarajan, M. Antibacterial behaviour of *Vitex negundo* extract assisted ZnO nanoparticles against pathogenic bacteria. *J. Photochem. Photobiol. B, Biol.* **2015**, *146*, 52-57, https://doi.org/10.1016/j.jphotobiol.2015.02.020.
72. Dobrucka, R.; Długaszewska, J. Biosynthesis and antibacterial activity of ZnO nanoparticles using *Trifolium pratense* flower extract. *Saudi J. Biol. Sci.* **2016**, *23*, 517-523, https://doi.org/10.1016/j.sjbs.2015.05.016.
73. Karam, S.T.; Abdulrahman, A.F. Green Synthesis and Characterization of ZnO Nanoparticles by Using Thyme Plant Leaf Extract. *Photonics* **2022**, *9*, 594, https://doi.org/10.3390/photonics9080594.
74. Hayat, K.; Din, I.U.; Alam, K.; Khan, F.U.; Khan, M.; Mohamed, H.I. Green synthesis of zinc oxide nanoparticles using plant extracts of *Fumaria officinalis* and *Peganum harmala* and their antioxidant and antibacterial activities. *Biomass Conv. Bioref.* **2025**, *15*, 9565-9579, https://doi.org/10.1007/s13399-024-05804-x.
75. Gurusamy, M.; Sellavel, M.; Kuppuvelsamy, V. A sustainable green synthesis for photocatalytic and antibacterial activity of zinc oxide nanoparticles using *Cucumis maderaspatanus leaf extract*. *Desalin. Water Treat.* **2024**, *319*, 100457, https://doi.org/10.1016/j.dwt.2024.100457.
76. Chowdhury, A.S.; Islam, M.M.; Ghosh, A. Green Synthesis and Characterization of ZnO Nanoparticles from the Extract of *Tagetes erecta* Leaves. Proceedings of the 14th International Conference on Mechanical Engineering (ICME 2023), BUET, Dhaka, Bangladesh, 18-19 December 2023; SSRN: **2024**, https://doi.org/10.2139/ssrn.4859507.
77. Omar, S.T.; Ali, w.K. Effects of zinc oxide nanoparticles (ZnO NPs) synthesized from different plant leaf extracts on mealworm larvae Tenebrio molitor L.,1758 (Tenebrionidae: Coleopetera). *Zanco J. Pure Appl. Sci.* **2024**, *36*, 7-18,https://doi.org/10.21271/ZJPAS.36.3.2.
78. Irshad, M.A.; Abdullah; Latif, M.; Nasim, I.; Nawaz, R.; Zahoor, A.F.; Al-Mutairi, A.A.; Al-Hussain, S.A.; Irfan, A.; Zaki, M.E.A. Efficient chromium removal from leather industrial wastewater in batch experimental study: Green synthesis and characterization of zinc oxide nanoparticles using *Ficus benghalensis* extracts. *Ecotoxicol. Environ. Saf.* **2024**, *281*, 116616, https://doi.org/10.1016/j.ecoenv.2024.116616.
79. Mongy, Y.; Shalaby, T. Green synthesis of zinc oxide nanoparticles using *Rhus coriaria* extract and their anticancer activity against triple-negative breast cancer cells. *Sci. Rep.* **2024**, *14*, 13470, https://doi.org/10.1038/s41598-024-63258-7.
80. Rashid, M.U.; Shah, S.J.; Attacha, S.; Khan, L.; Saeed, J.; Shah, S.T.; Mohamed, H.I. Green Synthesis and Characterization of Zinc Oxide Nanoparticles Using *Citrus limetta* Peels Extract and Their Antibacterial Activity Against Brown and Soft Rot Pathogens and Antioxidant Potential. *Waste Biomass Valor.* **2024**, *15*, 3351-3366, https://doi.org/10.1007/s12649-023-02389-w.
81. R, G.; Yuvaraj, D.; Reddy, G.K.; Shangar, S.N.; Vijayakumar, V.; Iyyappan, J. Zinc oxide nanoparticles from leaf extract of *Eclipta prostrata*: Biosynthesis and characterization towards potential agent against film forming bacteria in metal working fluids. *Environ. Chem. Ecotoxicol.* **2024**, *6*, 206-215, https://doi.org/10.1016/j.enceco.2024.06.001.
82. Fakhar-e-Alam, M.; Amjad, I.; Saadullah, M.; Tahir, M.; Jawad, M.; Asif, M.; Atif, M.; Zara, S.; Rashad, M. Antitumor activity of zinc oxide nanoparticles fused with green extract of *Nigella sativa*. *J. Saudi Chem. Soc.* **2024**, *28*, 101814, https://doi.org/10.1016/j.jscs.2024.101814.
83. Perumal, P.; Sathakkathulla, N.A.; Kumaran, K.; Ravikumar, R.; Selvaraj, J.J.; Nagendran, V.; Gurusamy, M.; Shaik, N.; Gnanavadivel Prabhakaran, S.; Suruli Palanichamy, V.; Ganesan, V.; Thiraviam, P.P.; Gunalan, S.; Rathinasamy, S. Green synthesis of zinc oxide nanoparticles using aqueous extract of shilajit and their anticancer activity against HeLa cells. *Sci. Rep.* **2024**, *14*, 2204, https://doi.org/10.1038/s41598-024-52217-x.
84. Harikrishnan, A.; Ramalingam, B.; Nadeem, A.; Ramachandran, B.; Veena, V.K.; Muthupandian, S. Eco-friendly synthesis of zinc oxide nanoparticles (ZnOnps) from *Piper betel* leaf extract: spectral

characterization and its application on plant growth parameters in maize, fenugreek and red gram. *Mater. Technol.* **2024**, *39*, 2298547, https://doi.org/10.1080/10667857.2023.2298547.

85. Poojary, P.V.; Sarkar, S.; Poojary, A.A.; Mallya, P.; Selvaraj, R.; Koteshwara, A.; Aranjani, J.M.; Lewis, S. Novel anti-dandruff shampoo incorporated with ketoconazole-coated zinc oxide nanoparticles using green tea extract. *J. Cosmet. Dermatol.* **2024**, *23*, 563-575, https://doi.org/10.1111/jocd.16027.
86. Al Rahbi, A.S.; Al Mawali, A.H.; Al Rawahi, S.S.; Al Dighishi, R.K.; Al Abri, F.A.; Ahmed, A.; Rahman, S. Green synthesis of zinc oxide nanoparticles from *Salvadora persica* leaf extract: Characterization and studying methyl orange removal by adsorption. *Water Pract. Technol.* **2024**, *19*, 1219-1231, https://doi.org/10.2166/wpt.2024.042.
87. Orie, K.J.; Okocha, B.I. Biosynthesis and antimicrobial studies of zinc oxide nanoparticles of *Vernonia amygdalina* Leaf with varying concentration of zinc oxide. *Inorg. Chem. Commun.* **2024**, *162*, 112178, https://doi.org/10.1016/j.inoche.2024.112178.
88. Gangwar, J.; Balasubramanian, B.; Pratap Singh, A.; Meyyazhagan, A.; Pappuswamy, M.; Alanazi, A.M.; Rengasamy, K.R.R.; Kadanthottu Sebastian, J. Biosynthesis of zinc oxide nanoparticles mediated by *Strobilanthes hamiltoniana*: Characterizations, and its biological applications. *Kuwait J. Sci.* **2024**, *51*, 100102, https://doi.org/10.1016/j.kjs.2023.07.008.
89. Lamichhane, Y.R.; Parajuli, K.; Pradhanang, S.S. Preparation of zinc oxide nanoparticles using Citrus sinensis fruit peel aqueous extract and its antimicrobial study. *Sci. World* **2024**, *17*, 99-105, https://doi.org/10.3126/sw.v17i17.66441.
90. Ighalo, J.O.; Sagboye, P.A.; Umenweke, G.; Ajala, O.J.; Omoarukhe, F.O.; Adeyanju, C.A.; Ogunniyi, S.; Adeniyi, A.G. CuO nanoparticles (CuO NPs) for water treatment: A review of recent advances. *Environ. Nanotechnol. Monit. Manag.* **2021**, *15*, 100443, https://doi.org/10.1016/j.enmm.2021.100443.
91. Ramesh, M. CuO as efficient photo catalyst for photocatalytic decoloration of wastewater containing Azo dyes. *Water Pract. Technol.* **2021**, *16*, 1078-1090, https://doi.org/10.2166/wpt.2021.067.
92. Sibhatu, A.K.; Weldegebrieal, G.K.; Sagadevan, S.; Tran, N.N.; Hessel, V. Photocatalytic activity of CuO nanoparticles for organic and inorganic pollutants removal in wastewater remediation. *Chemosphere* **2022**, *300*, 134623, https://doi.org/10.1016/j.chemosphere.2022.134623.
93. Pandey, M.; Singh, M.; Wasnik, K.; Gupta, S.; Patra, S.; Gupta, P.S.; Pareek, D.; Chaitanya, N.S.N.; Maity, S.; Reddy, A.B.M.; Tilak, R.; Paik, P. Targeted and Enhanced Antimicrobial Inhibition of Mesoporous ZnO–Ag_2O/Ag, ZnO–CuO, and ZnO–SnO_2 Composite Nanoparticles. *ACS Omega* **2021**, *6*, 31615-31631, https://doi.org/10.1021/ACSOMEGA.1C04139.
94. Govindasamy, G.A.; Mydin, R.B.S.M.N.; Sreekantan, S.; Harun, N.H. Compositions and antimicrobial properties of binary ZnO–CuO nanocomposites encapsulated calcium and carbon from *Calotropis gigantea* targeted for skin pathogens. *Sci. Rep.* **2021**, *11*, 99, https://doi.org/10.1038/s41598-020-79547-w.
95. Zheng, Y.; Zheng, S.; Xue, H.; Pang, H. Metal-Organic Frameworks/Graphene-Based Materials: Preparations and Applications. *Adv. Funct. Mater.* **2018**, *28*, 1804950, https://doi.org/10.1002/ADFM.201804950.
96. Xu, J.; He, S.; Zhang, H.; Huang, J.; Lin, H.; Wang, X.; Long, J. Layered metal–organic framework/graphene nanoarchitectures for organic photosynthesis under visible light. *J. Mater. Chem. A* **2015**, *3*, 24261-24271, https://doi.org/10.1039/C5TA06838J.
97. Pujalté, I.; Passagne, I.; Brouillaud, B.; Tréguer, M.; Durand, E.; Ohayon-Courtès, C.; L'Azou, B. Cytotoxicity and oxidative stress induced by different metallic nanoparticles on human kidney cells. *Part. Fibre Toxicol.* **2011**, *8*, 10, https://doi.org/10.1186/1743-8977-8-10.
98. Alhadlaq, H.A.; Akhtar, M.J.; Ahamed, M. Zinc ferrite nanoparticle-induced cytotoxicity and oxidative stress in different human cells. *Cell Biosci.* **2015**, *5*, 55, https://doi.org/10.1186/S13578-015-0046-6.
99. Nigussie, A.; Ananda Murthy, H.C.; Bedassa, A. A Review on Synthesis, Characterization and Photocatalytic Applications of Copper Oxide Nanostructures. *Res. J. Chem. Environ.* **2021**, *25*, 202-227.
100. Hsu, C.-L.; Chen, K.-C.; Tsai, T.-Y.; Hsueh, T.-J. Fabrication of gas sensor based on p-type ZnO nanoparticles and n-type ZnO nanowires. *Sens. Actuator B-Chem.* **2013**, *182*, 190-196, https://doi.org/10.1016/j.snb.2013.03.002.
101. Varudkar, H.A.; Umadevi, G.; Nagaraju, P.; Dargad, J.S.; Mote, V.D. Fabrication of Al-doped ZnO nanoparticles and their application as a semiconductor-based gas sensor for the detection of ammonia. *J. Mater. Sci.: Mater. Electron.* **2020**, *31*, 12579-12585, https://doi.org/10.1007/S10854-020-03808-7.

102. Parashar, M.; Shukla, V.K.; Singh, R. Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications. *J. Mater. Sci.: Mater. Electron.* **2020**, *31*, 3729-3749, https://doi.org/10.1007/S10854-020-02994-8.
103. Alagiri, M.; Ponnusamy, S.; Muthamizhchelvan, C. Synthesis and characterization of NiO nanoparticles by sol–gel method. *J. Mater. Sci.: Mater. Electron.* **2012**, *23*, 728-732, https://doi.org/10.1007/S10854-011-0479-6.
104. Hasnidawani, J.N.; Azlina, H.N.; Norita, H.; Bonnia, N.N.; Ratim, S.; Ali, E.S. Synthesis of ZnO Nanostructures Using Sol-Gel Method. *Procedia Chem.* **2016**, *19*, 211-216, https://doi.org/10.1016/j.proche.2016.03.095.
105. Chen, D.-H.; He, X.-R. Synthesis of nickel ferrite nanoparticles by sol-gel method. *Mater. Res. Bull.* **2001**, *36*, 1369-1377, https://doi.org/10.1016/S0025-5408(01)00620-1.
106. Dubey, R.S.; Rajesh, Y.B.R.D.; More, M.A. Synthesis and Characterization of SiO_2 Nanoparticles via Sol-gel Method for Industrial Applications. *Mater. Today Proc.* **2015**, *2*, 3575-3579, https://doi.org/10.1016/j.matpr.2015.07.098.
107. Teoh, L.G.; Li, K.-D. Synthesis and Characterization of NiO Nanoparticles by Sol–Gel Method. *Mater. Trans.* 2012, *53*, 2153-2140, https://doi.org/10.2320/matertrans.M2012244.
108. Zorkipli, N.N.M.; Kaus, N.H.M.; Mohamad, A.A. Synthesis of NiO Nanoparticles through Sol-gel Method. *Procedia Chem.* **2016**, *19*, 626-631, https://doi.org/10.1016/j.proche.2016.03.062.
109. Xu, J.; Yang, H.; Fu, W.; Du, K.; Sui, Y.; Chen, J.; Zeng, Y.; Li, M.; Zou, G. Preparation and magnetic properties of magnetite nanoparticles by sol–gel method. *J. Magn. Magn. Mater.* **2007**, *309*, 307-311, https://doi.org/10.1016/j.jmmm.2006.07.037.
110. Andualem, W.W.; Sabir, F.K.; Mohammed, E.T.; Belay, H.H.; Gonfa, B.A. Synthesis of Copper Oxide Nanoparticles Using Plant Leaf Extract of *Catha edulis* and Its Antibacterial Activity. *J. Nanotechnol.* **2020**, *2020*, 2932434, https://doi.org/10.1155/2020/2932434.
111. Velsankar, K.; R.M, A.K.; R, P.; V, M.; Sudhahar, S. Green synthesis of CuO nanoparticles via *Allium sativum* extract and its characterizations on antimicrobial, antioxidant, antilarvicidal activities. *J. Environ. Chem. Eng.* **2020**, *8*, 104123, https://doi.org/10.1016/j.jece.2020.104123.
112. Sharma, J.K.; Akhtar, M.S.; Ameen, S.; Srivastava, P.; Singh, G. Green synthesis of CuO nanoparticles with leaf extract of *Calotropis gigantea* and its dye-sensitized solar cells applications. *J. Alloys Compd.* **2015**, *632*, 321-325, https://doi.org/10.1016/j.jallcom.2015.01.172.
113. Velsankar, K.; Vinothini, V.; Sudhahar, S.; Kumar, M.K.; Mohandoss, S. Green Synthesis of CuO nanoparticles via *Plectranthus amboinicus* leaves extract with its characterization on structural, morphological, and biological properties. *Appl. Nanosci.* **2020**, *10*, 3953-3971, https://doi.org/10.1007/S13204-020-01504-W.
114. Gebremedhn, K.; Kahsay, M.H.; Aklilu, M. Green synthesis of CuO nanoparticles using leaf extract of Catha edulis and its antibacterial activity. *J. Pharm. Pharmacol.* **2019**, *7*, 327-342.
115. Chowdhury, R.; Khan, A.; Rashid, M.H. Green synthesis of CuO nanoparticles using *Lantana camara* flower extract and their potential catalytic activity towards the aza-Michael reaction. *RSC Adv.* **2020**, *10*, 14374-14385, https://doi.org/10.1039/D0RA01479F.
116. Nouren, S.; Bibi, I.; Kausar, A.; Sultan, M.; Nawaz Bhatti, H.; Safa, Y.; Sadaf, S.; Alwadai, N.; Iqbal, M. Green synthesis of CuO nanoparticles using *Jasmin sambac* extract: Conditions optimization and photocatalytic degradation of Methylene Blue dye. *J. King Saud Univ. Sci.* **2024**, *36*, 103089, https://doi.org/10.1016/j.jksus.2024.103089.
117. Ikhioya, I.L.; Onoh, E.U.; Nkele, A.C.; Abor, B.C.; Obitte, B.C.N.; Maaza, M.; Ezema, F.I. The The Green Synthesis of Copper Oxide Nanoparticles Using the Moringa Oleifera Plant and its Subsequent Characterization for Use in Energy Storage Applications. *East Eur. J. Phys.* **2023**, 162-172, https://doi.org/10.26565/2312-4334-2023-1-20.
118. Thandapani, G.; Arthi, K.; Pazhanisamy, P.; John, J.J.; Vinothini, C.; Rekha, V.; Santhanalakshmi, K.; Sekar, V. Green synthesis of copper oxide nanoparticles using *Spinacia oleracea* leaf extract and evaluation of biological applications: Antioxidant, antibacterial, larvicidal and biosafety assay. *Mater. Today Commun.* **2023**, *34*, 105248, https://doi.org/10.1016/j.mtcomm.2022.105248.
119. Ramasubbu, K.; Padmanabhan, S.; Al-Ghanim, K.A.; Nicoletti, M.; Govindarajan, M.; Sachivkina, N.; Rajeswari, V.D. Green Synthesis of Copper Oxide Nanoparticles Using *Sesbania grandiflora* Leaf Extract and Their Evaluation of Anti-Diabetic, Cytotoxic, Anti-Microbial, and Anti-Inflammatory Properties in an In-Vitro Approach. *Fermentation* **2023**, *9*, 332, https://doi.org/10.3390/fermentation9040332.

120. Siddiqui, V.U.; Ansari, A.; Chauhan, R.; Siddiqi, W.A. Green synthesis of copper oxide (CuO) nanoparticles by *Punica granatum* peel extract. *Mater. Today Proc.* **2021**, *36*, 751-755, https://doi.org/10.1016/j.matpr.2020.05.504.
121. Alhalili, Z. Green synthesis of copper oxide nanoparticles CuO NPs from *Eucalyptus Globoulus* leaf extract: Adsorption and design of experiments. *Arab. J. Chem.* **2022**, *15*, 103739, https://doi.org/10.1016/j.arabjc.2022.103739.
122. Ramzan, M.; Obodo, R.M.; Mukhtar, S.; Ilyas, S.Z.; Aziz, F.; Thovhogi, N. Green synthesis of copper oxide nanoparticles using Cedrus deodara aqueous extract for antibacterial activity. *Mater. Today Proc.* **2021**, *36*, 576-581, https://doi.org/10.1016/j.matpr.2020.05.472.
123. Atri, A.; Echabaane, M.; Bouzidi, A.; Harabi, I.; Soucase, B.M.; Ben Chaâbane, R. Green synthesis of copper oxide nanoparticles using *Ephedra Alata* plant extract and a study of their antifungal, antibacterial activity and photocatalytic performance under sunlight. *Heliyon* **2023**, *9*, e13484, https://doi.org/10.1016/j.heliyon.2023.e13484.
124. Vishveshvar, K.; Aravind Krishnan, M.V.; Haribabu, K.; Vishnuprasad, S. Green Synthesis of Copper Oxide Nanoparticles Using Ixiro coccinea Plant Leaves and its Characterization. *BioNanoScience* **2018**, *8*, 554-558, https://doi.org/10.1007/s12668-018-0508-5.
125. Naika, H.R.; Lingaraju, K.; Manjunath, K.; Kumar, D.; Nagaraju, G.; Suresh, D.; Nagabhushana, H. Green synthesis of CuO nanoparticles using *Gloriosa superba* L. extract and their antibacterial activity. *J. Taibah Univ. Sci.* **2015**, *9*, 7-12, https://doi.org/10.1016/j.jtusci.2014.04.006.
126. Javid-Naderi, M.J.; Sabouri, Z.; Jalili, A.; Zarrinfar, H.; Samarghandian, S.; Darroudi, M. Green synthesis of copper oxide nanoparticles using okra (*Abelmoschus esculentus*) fruit extract and assessment of their cytotoxicity and photocatalytic applications. *Environ. Technol. Innov.* **2023**, *32*, 103300, https://doi.org/10.1016/j.eti.2023.103300.
127. Kaur, H.; Kumar, S.; Bouzid, G. Exploring the role of different phytochemicals on the morphological variations of metal and metal oxide nanomaterials for biomedical application. *Interactions* **2024**, *245*, 234, https://doi.org/10.1007/S10751-024-02088-5.
128. Ovais, M.; Khalil, A.T.; Islam, N.U.; Ahmad, I.; Ayaz, M.; Saravanan, M.; Shinwari, Z.K.; Mukherjee, S. Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. *Appl. Microbiol. Biotechnol.* **2018**, *102*, 6799-6814, https://doi.org/10.1007/S00253-018-9146-7.
129. Kredy, H.M. The effect of pH, temperature on the green synthesis and biochemical activities of silver nanoparticles from Lawsonia inermis extract. *J. Pharm. Sci. Res.* **2018**, *10*, 2022-2026.
130. Pinto, R.J.B.; Lucas, J.M.F.; Morais, M.P.; Santos, S.A.O.; Silvestre, A.J.D.; Marques, P.A.A.P.; Freire, C.S.R. Demystifying the morphology and size control on the biosynthesis of gold nanoparticles using *Eucalyptus globulus* bark extract. *Ind. Crops Prod.* **2017**, *105*, 83-92, https://doi.org/10.1016/j.indcrop.2017.05.003.
131. Githiori, J.B.; Athanasiadou, S.; Thamsborg, S.M. Use of plants in novel approaches for control of gastrointestinal helminths in livestock with emphasis on small ruminants. *Vet. Parasitol.* **2006**, *139*, 308-320, https://doi.org/10.1016/j.vetpar.2006.04.021.
132. Cheesman, M.J.; Ilanko, A.; Blonk, B.; Cock, I.E. Developing New Antimicrobial Therapies: Are Synergistic Combinations of Plant Extracts/Compounds with Conventional Antibiotics the Solution? *Pharmacogn. Rev.* **2017**, *11*, 57-72, https://doi.org/10.4103/phrev.phrev_21_17.
133. Gebreslassie, Y.T.; Gebretnsae, H.G. Green and Cost-Effective Synthesis of Tin Oxide Nanoparticles: A Review on the Synthesis Methodologies, Mechanism of Formation, and Their Potential Applications. *Nanoscale Res. Lett.* **2021**, *16*, 97, https://doi.org/10.1186/s11671-021-03555-6.
134. Naz, S.; Gul, A.; Zia, M.; Javed, R. Synthesis, biomedical applications, and toxicity of CuO nanoparticles. *Appl. Microbiol. Biotechnol.* **2023**, *107*, 1039-1061, https://doi.org/10.1007/S00253-023-12364-Z.
135. Grigore, M.E.; Biscu, E.R.; Holban, A.M.; Gestal, M.C.; Grumezescu, A.M. Methods of Synthesis, Properties and Biomedical Applications of CuO Nanoparticles. *Pharmaceuticals* **2016**, *9*, 75, https://doi.org/10.3390/ph9040075.
136. Madkour, L.H. Nanoparticle-Based Drug Delivery in Cancer Treatment, 1st Edition; CRC Press: Boca Raton, **2022**; https://doi.org/10.1201/9781003229674.
137. Sahu, T.; Ratre, Y.K.; Chauhan, S.; Bhaskar, L.V.K.S.; Nair, M.P.; Verma, H.K. Nanotechnology based drug delivery system: Current strategies and emerging therapeutic potential for medical science. *Journal of Drug Delivery Science and Technology* **2021**, *63*, 102487, https://doi.org/10.1016/j.jddst.2021.102487.

138. Siafaka, P.I.; Üstündağ Okur, N.; Karavas, E.; Bikiaris, D.N. Surface Modified Multifunctional and Stimuli Responsive Nanoparticles for Drug Targeting: Current Status and Uses. *Int. J. Mol. Sci.* **2016**, *17*, 1440, https://doi.org/10.3390/ijms17091440.
139. Nienhaus, K.; Wang, H.; Nienhaus, G.U. Nanoparticles for biomedical applications: exploring and exploiting molecular interactions at the nano-bio interface. *Mater. Today Adv.* **2020**, *5*, 100036, https://doi.org/10.1016/j.mtadv.2019.100036.
140. Vass, I.Z.; Deák, Z.; Paul, K.; Kovács, S.; Vass, I. Interaction of nanoparticles with biological systems. *Acta Biologica Szegediensis* **2015**, *59*, 225-245.
141. Shume, W.M.; Murthy, H.C.A.; Zereffa, E.A. A Review on Synthesis and Characterization of Ag2O Nanoparticles for Photocatalytic Applications. *J. Chem.* **2020**, *2020*, 5039479, https://doi.org/10.1155/2020/5039479.
142. Rafeeq, H.; Hussain, A.; Ambreen, A.; Waqas, M.; Bilal, M.; Iqbal, H.M.N. Functionalized nanoparticles and their environmental remediation potential: a review. *J. Nanostruct. Chem.* **2022**, *12*, 1007-1031, https://doi.org/10.1007/s40097-021-00468-9.
143. Aguilar-Pérez, K.M.; Avilés-Castrillo, J.I.; Ruiz-Pulido, G.; Medina, D.I.; Parra-Saldivar, R.; Iqbal, H.M.N. Nanoadsorbents in focus for the remediation of environmentally-related contaminants with rising toxicity concerns. *Sci. Total Environ.* **2021**, *779*, 146465, https://doi.org/10.1016/j.scitotenv.2021.146465.
144. Khan, S.; Naushad, M.; Al-Gheethi, A.; Iqbal, J. Engineered nanoparticles for removal of pollutants from wastewater: Current status and future prospects of nanotechnology for remediation strategies. *Environ. Chem. Eng.* **2021**, *9*, 106160, https://doi.org/10.1016/j.jece.2021.106160.
145. Lozhkomoev, A.S.; Bakina, O.V.; Pervikov, A.V.; Kazantsev, S.O.; Glazkova, E.A. Synthesis of CuO–ZnO composite nanoparticles by electrical explosion of wires and their antibacterial activities. *J. Mater. Sci.: Mater. Electron.* **2019**, *30*, 13209-13216, https://doi.org/10.1007/S10854-019-01684-4.
146. Sakib, A.A.M.; Masum, S.M.; Hoinkis, J.; Islam, R.; Molla, M.A.I. Synthesis of CuO/ZnO Nanocomposites and Their Application in Photodegradation of Toxic Textile Dye. *J. Compos. Sci.* **2019**, *3*, 91, https://doi.org/10.3390/jcs3030091.
147. Mishra, S.R.; Ahmaruzzaman, M. CuO and CuO-based nanocomposites: Synthesis and applications in environment and energy. *Sustain. Mater. Technol.* **2022**, *33*, e00463, https://doi.org/10.1016/j.susmat.2022.e00463.
148. Maruthupandy, M.; Zuo, Y.; Chen, J.-S.; Song, J.-M.; Niu, H.-L.; Mao, C.-J.; Zhang, S.-Y.; Shen, Y.-H. Synthesis of metal oxide nanoparticles (CuO and ZnO NPs) via biological template and their optical sensor applications. *Appl. Surf. Sci.* **2017**, *397*, 167-174, https://doi.org/10.1016/j.apsusc.2016.11.118.
149. Puspasari, V.; Ridhova, A.; Hermawan, A.; Amal, M.I.; Khan, M.M. ZnO-based antimicrobial coatings for biomedical applications. *Bioprocess Biosyst. Eng.* **2022**, *45*, 1421-1445, https://doi.org/10.1007/s00449-022-02733-9.
150. Muthuchamy, M.; Muneeswaran, T.; Rajivgandhi, G.; Franck, Q.; Muthusamy, A.; Ji-Ming, S. Biologically synthesized copper and zinc oxide nanoparticles for important biomolecules detection and antimicrobial applications. *Mater. Today Commun.* **2020**, *22*, 100766, https://doi.org/10.1016/j.mtcomm.2019.100766.
151. Takshi, A.; Aljafari, B.; Kareri, T.; Stefanakos, E. A Critical Review on the Voltage Requirement in Hybrid Cells with Solar Energy Harvesting and Energy Storage Capability. *Batteries Supercaps* **2021**, *4*, 252-267, https://doi.org/10.1002/BATT.202000223.
152. Clarissa, W.H.-Y.; Chia, C.H.; Zakaria, S.; Evyan, Y.C.-Y. Recent advancement in 3-D printing: nanocomposites with added functionality. *Prog. Addit. Manuf.* **2022**, *7*, 325-350, https://doi.org/10.1007/S40964-021-00232-Z.
153. Nadgorny, M.; Ameli, A. Functional Polymers and Nanocomposites for 3D Printing of Smart Structures and Devices. *ACS Appl. Mater. Interfaces* **2018**, *10*, 17489–17507, https://doi.org/10.1021/ACSAMI.8B01786.
154. Sainz, V.; Conniot, J.; Matos, A.I.; Peres, C.; Zupanǒiǒ, E.; Moura, L.; Silva, L.C.; Florindo, H.F.; Gaspar, R.S. Regulatory aspects on nanomedicines. *Biochem. Biophys. Res. Commun.* **2015**, *468*, 504-510, https://doi.org/10.1016/j.bbrc.2015.08.023.
155. Wei, H.; Rodriguez, K.; Renneckar, S.; Vikesland, P.J. Environmental science and engineering applications of nanocellulose-based nanocomposites. *Environ. Sci.: Nano* **2014**, *1*, 302-316, https://doi.org/10.1039/C4EN00059E.

156. Handy, R.D.; Owen, R.; Valsami-Jones, E. The ecotoxicology of nanoparticles and nanomaterials: current status, knowledge gaps, challenges, and future needs. *Ecotoxicology* **2008**, *17*, 315-325, https://doi.org/10.1007/S10646-008-0206-0.
157. Lai, R.W.S.; Yeung, K.W.Y.; Yung, M.M.N.; Djurišić, A.B.; Giesy, J.P.; Leung, K.M.Y. Regulation of engineered nanomaterials: current challenges, insights and future directions. *Environ. Sci. Pollut. Res.* **2018**, *25*, 3060-3077, https://doi.org/10.1007/S11356-017-9489-0.

Publisher's Note & Disclaimer