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Review Article

Sustainable Nanotechnology : A Comprehensive Review of Recent Advancements in Green Synthesis Techniques for ZnO Nanoparticles and Their Diverse Applications

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Abstract— Zinc oxide [ZnO] nanoparticles have drawn significant attention due to their numerous promising applications in a variety of domains like medicine, environmental studies, and electronics. Generally, the synthesis of ZnO nanoparticles has traditionally involved chemical methods that often require toxic chemicals and expensive equipment. However, these conventional methods raises concerns about the impact of on the environment and their biocompatibility, driving a shift in the intrest towards the green/ biological synthesis of ZnO nanoparticles. Green synthesis is less hazardous aproach because it uses plant extracts from leaves, flowers, fruits, bark, and peels, reducing the need for potentially hazardous substances. This environmentally friendly process not only reduces harm but also enhances ZnO nanoparticles biocompatibility, broadening the range of possible applications in various fields. The review covers the recent developments in the environmental friendly green synthesis of ZnO nanoparticles. The article explores various techniques for synthesis of nanoparticles and highlights the influence of plant-mediated processes on the their size, structure, and morphologies. In addition, the paper discusses several characterization techniques which are necessary to understand the properties of nanoparticles synthesized by sustainable methods. The review discusses multiple applications of these nanoparticles, highlighting their role in advancing towards sustainable & eco-conscious future.

Keywords— Zinc oxide, Green synthesis, Nanoparticles, Antimicrobial activity, Photocatalytic

1. Introduction

The field of nanotechnology has grown significantly during the past century. Furthermore, nanotechnology is at present the subject of a multitude of types of research, in either a direct or indirect way [1]. Nanoparticles are particles that have a size range of 1 to 100 nanometers. When particles are reduced to the nanoscale, materials display unique chemical & physical properties due to their high ratio of surface area to volume [2]. Nanoparticles display distinctive qualities from those of their bulk counterparts which makes them suitable for a wide range of uses [3].Nanoparticles can be classified into various categories based on their composition and characteristics, including, Metal or metal oxide nanoparticles, carbon based NPs, semiconductor NPs, , Polymeric NPs, lipid based NPs and ceramic NPs. Metal oxide nanoparticles are widely used in several cutting-edge applications, such as Catalysis, Optoelectronics materials, heavy metal removal in industrial wastewater, antiviral agents, electrochemical energy storage, Antioxidants, photocatalytic degradation, drug delivery & diagnosis, cosmetics and skin care, anti-inflammatory agents and Antimicrobial agents in surfaces of building structures [4-14]. Zinc oxide nanoparticles have attracted a lot of attention recently because of their distinctive characteristics and extensive range of dievrse applications. Zinc oxide nanoparticles have exceptional optical, electrical, and antimicrobial characteristics, making them highly valuable in different domains, such as environmental science, electronics, and medicine [15-17]. Their high ratio of surface area to volume and semiconductor characteristics facilitate effective photocatalytic activity [18]. It is helpful for decomposing contaminants and disinfecting water in cleaning up the environment. Developments in ZnO nanoparticle synthesis techniques are being made with the goal of improving the material's stability, reactivity, and application, which will boost its use across scientific and industrial domains. For commercial application, ZnO nanoparticles can be produced chemically or mechanically. However, environmental problems raised by these methods have received worldwide concern [19]. Nanoparticles produced through traditional methods often have restricted applications in clinical settings because of their associated toxicity and the use of hazardous chemicals in their production process [20]. Utilizing plant extracts can boost the bioactivity of the nanoparticles, providing additional functionalities. Additionally, employing plant extract in the synthesis of nanoparticles has the advantage of their accessibility, safety, and large variety of metabolites, which include antioxidants, nucleotides, and vitamins. [21]. This review aims to provide a detailed analysis of the available techniques employed for the synthesis of ZnO nanoparticles utilizing extracts of different plant parts such as leaves, flowers, seeds, stems, bark, fruits and roots. Additionally, the review will explore the various applications of these green-synthesized ZnO nanoparticles across multiple fields. This study aims to highlight ZnO nanoparticles' potential for advancing the field of nanotechnology while promoting sustainability. We aim to encourage further research and innovation in green nanotechnology, paving the way for future developments which promote the objectives of global sustainability.

2. Methods of synthesis of ZnO Nanoparticles :

There are several methods to synthesize nanoparticles. The bottom-up method works with building up nanomaterials from the atomic scale, whereas the top-down aproach focuses on reducing the particle from micro to nanoscale [22].

2.1 Physical Methods

Ball Milling

The ball milling method is one of the physical top-down approach used for the synthesis of nanoparticles. This technology uses high-energy balls in a revolving or vibrating ball mill to mechanically reduce bulk materials to nanoscale sizes. Particles break down into smaller sizes as a result of frequent collisions between the balls and the substance [23]. ZnO nanoparticles can be synthesized by this method by precisely controlling the milling parameters, including milling speeds, processing time and the type of milling apparatus used [24]. Studies has been reported in which ZnO nanoparticles [ZnO NPs] are synthesized using a ball-milling approach at different calcined temperatures. The ZnO NPs were then characterized using a variety of characterization techniques [25, 26]

Thermal Evaporation

The thermal evaporation method is a physical vapor deposition [PVD] technique used for the synthesis of nanoparticles. This method involves heating bulk material to a high temperature and evaporating it in a vacuum chamber. Following their vaporization, the atoms or molecules condense onto a colder substrate to create thin films or nanoparticles [27, 28]. Zinc oxide nanoparticles with different morphologies have been synthesized via a thermal evaporation technique. The morphology of ZnO can be controlled by varying the evaporation pressure [29]. Using a variety of characterization methods, the impacts of selective control of process parameters on the morphological, structural, and optical properties of synthesized ZnO Nanoparticles are systematically investigated [30, 31]

Laser ablation

Laser ablation is a top-down physical method used to synthesize nanoparticles. A target substance is exposed to a high-energy laser beam, which causes the material to evaporate and produce a plasma plume. The plasma cools and forms nanoparticles [32, 33]. Zinc oxide nanoparticles are synthesized using laser-ablation method and are characterized by using different techniques. The size and shape of the nanoparticles can be controlled by controlling the ablation time and wavelength [34].

2.2 Chemical Methods

Sol-gel method

The sol-gel technique is a widely used bottom-up synthesis approach for creating nanoparticles with distinct chemical compositions. The creation of a homogenous sol from the precursors and its transformation into a gel form the foundation of the sol-gel process. The gel is subsequently dried, and the solvent is eliminated from the gel structure [35, 36]. The sol-gel method is based on inorganic polymerization processes. It contains four steps: hydrolysis, polycondensation, drying and thermal decomposition [37]. The sol-gel method is successfully used to synthesize zinc oxide nanoparticles with good crystallinity and their various properties and applications have been extensively reported in existing literature [38-41].

Precipitation method

The synthesis of nanoparticles by the precipitation method involves combining precipitating agent and metal salt solutions, which causes insoluble nanoparticles to form through nucleation and growth processes [42]. Synthesis & Characterization of ZnO Nanoparticles by using precipitation method has been reported in the literature. Furthermore, it has been reported that the precursor concentration, variation in pH, reaction time, synthesis temperature, calcination temperature, stirring time, and stirring speed all have an impact on the final structure, morphology and shape of the nanoparticles [43, 44].

Hydrothermal method

Hydrothermal synthesis of nanoparticles is a solution reaction-based approach. Chemical reactions occur in a liquid solution that is enclosed in a sealed container, subjected to high pressure and temperature. This process promotes the crystallization of nanoparticles [45]. The metal precursor goes through the hydrolysis and condensation processes during the hydrothermal synthesis, resulting in the formation of ionic and neutral species like metal hydroxide, oxides, and their complexes [46]. The process of synthesizing Zinc Oxide Nanoparticles with various shapes using hydrothermal synthesis is a well-known and frequently used method in many scientific investigations [47- 49].

Electrodeposition method

Electrodeposition is a technique used to create nanoparticles by applying an electric current to a solution containing metal ions, which then deposit onto a conductive surface. This technique allows precise control over various parameters related to nanoparticles such as shape, size and distributions by adjusting different variables such as voltage, time durations, and current densities [50, 51]. Various studies have reported the synthesis of ZnO Nps employing the electrodeposition method, achieving different morphologies under varying condition [52, 53]. The morphology of the ZnO nanoparticles can be precisely regulated by manipulating various parameters like temperature, deposition time, applied potential, and pH of the deposition bath [54, 55].

Chemical Vapour deposition

Nanoparticles can also be synthesized by using Chemical Vapor Deposition technique, where volatile precursors are vaporized and transported to a heated substrate, where they chemically react or form nanoparticles [56]. Numerous studies have reported on the synthesis of ZnO nanoparticles using Chemical Vapor Deposition [CVD] method, allowing for precise control over morphology and size of particles. This technique has been effective in producing ZnO Nanoparticles with different structures and morphologies [57-59].

3. Plant mediated synthesis of ZnO Nanoparticles:

Metal oxide nanoparticles are commonly synthesized by using chemical and physical methods. However, these processes often requires expensive equipment and involves toxic and harmful reducing agents which has adverse effect on environment [60]. Green synthesis of nanoparticles is an eco-friendly method that utilizes biological entities like plant extracts, fungi, algae, or bacteria etc. for synthesizing nanoparticles. Unlike traditional synthesis methods, this green synthesis technique involves non-toxic naturally occurring compounds which are renewable and abundantly available. Thus synthesis by this alternative approach is just not only biocompatible but also economical [61].

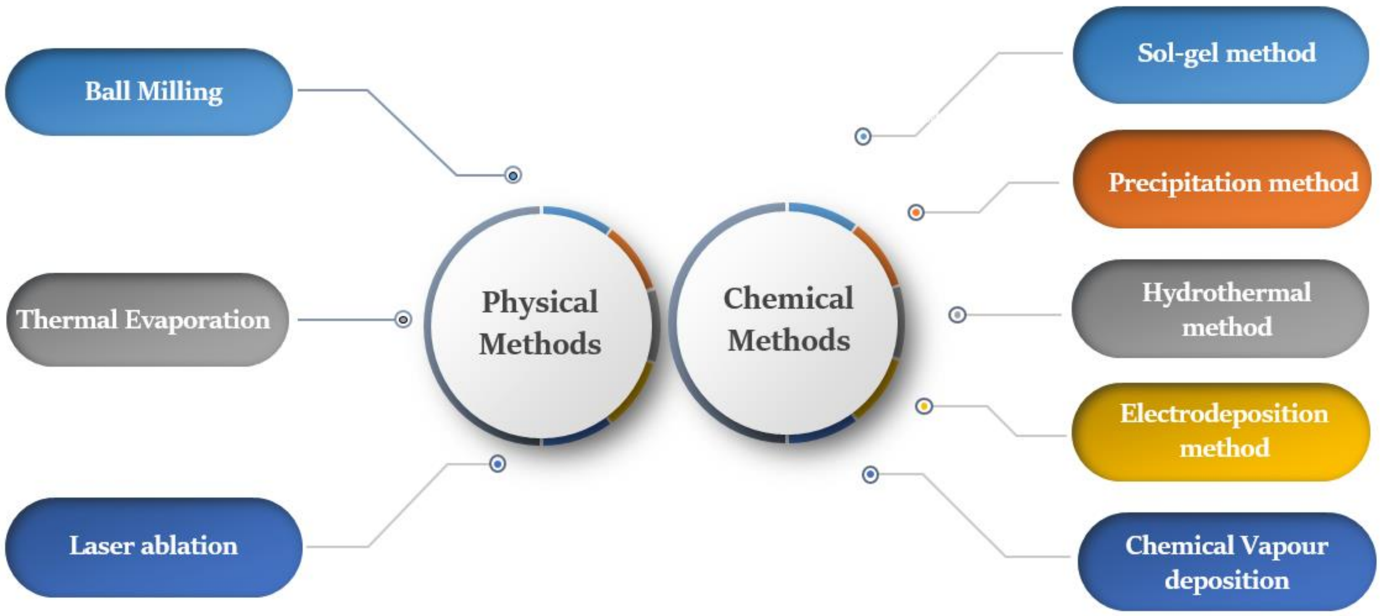

Figure 1. Overview of Conventional Synthesis Methods for ZnO Nanoparticles

The common method adopted for plant mediated synthesis of nanoparticles involves preparing a plant extract containing alkaloids, tannins, polysaccharides, flavonoids, terpenoids, or polyphenols by boiling or grinding different parts of the plant such as leaves, stems, fruits, bark, peels, or roots. After that, a solution containing metal ions, such as zinc acetate for ZnO nanoparticles is mixed with the plant extract. The plant extract is then combined with a solution containing metal ions, like zinc acetate for zinc oxide nanoparticles. In the presence of biomolecule of the plant extract, reduction of metal ions occurs and the formation of nanoparticles takes place. These biomolecules do not only involve in the reduction process but they often act as capping and stabilizing agent, preventing assemblage and enhancing their functionality. The intricacy of plant extracts makes it difficult to control the physicochemical properties of NPs, despite the fact that a good understanding of the biomolecules will be useful in the development of new green approaches. The morphological & structural characteristics of nanoparticles can be varied by altering the reactant composition/concentrations and condition of the reaction [62-66].

ZnO Nanoparticles synthesized using spinach leaves was studied for their potential to degrade wastewater. ZnO Nanoparticles were characterized using XRD, SEM, UV-Vis and TEM. FTIR, XPS, and EDXS for ZnO NP structural analysis. ZnO NPs from spinach leaves effectively break down wastewater in the presence of sunlight. Biosynthesised ZnO nanoparticles exhibit photocatalytic activity in the breakdown of wastewater [67]. While studying the plant-mediated ZnO NPs synthesis for eco-friendly water treatment applications it was explored that pH influences ZnO properties. Green synthesis of ZnO NPs using Sorghum seed at pH 11 was explored. Sorghum seed extract at pH 11 showed best photocatalytic degradation. pH influences ZnO NPs properties for efficient methylene blue degradation. ZnO

Nanoparticles synthesized with pH 11 have shown high degradation efficiency [68].

Green synthesis of ZnO nanoparticles using Sorghum panicle for photocatalytic degradation, antibacterial activity and phytotoxicity studies was conducted. Synthesised nanoparticles were characterised for stability, morphology, and thermal properties. ZnO nanoparticles synthesised using Sorghum panicle showed high photocatalytic degradation efficiency. An investigation on the effects of nanoparticle concentration on antibacterial activity revealed increased activity, 100% of the seeds germination rate with treated water was found in a phytotoxicity study [69]. Further, it was studied that co-doped ZnO NPs show improved degradation of methylene blue dye. Green synthesis of Ni-Mn co-doped ZnO NPs from orange peel extract showed improved photocatalytic activity, degrading 97% methylene blue. This study also reveals that doping concentration affects crystallite size, band gap, and photocatalytic activity [70]. Segun Abegunde et al. studied that ZnO nanoparticles synthesized from Nauclea latifolia fruit extract can have antimicrobial use. Prepared ZnO NPs were characterised using different methods, which include UV-Vis, FTIR, XRD, DLS, and TEM. Nauclea latifolia-ZnO NPs showed antibacterial properties and high antimicrobial potency against E. coli and S. aureus [71].

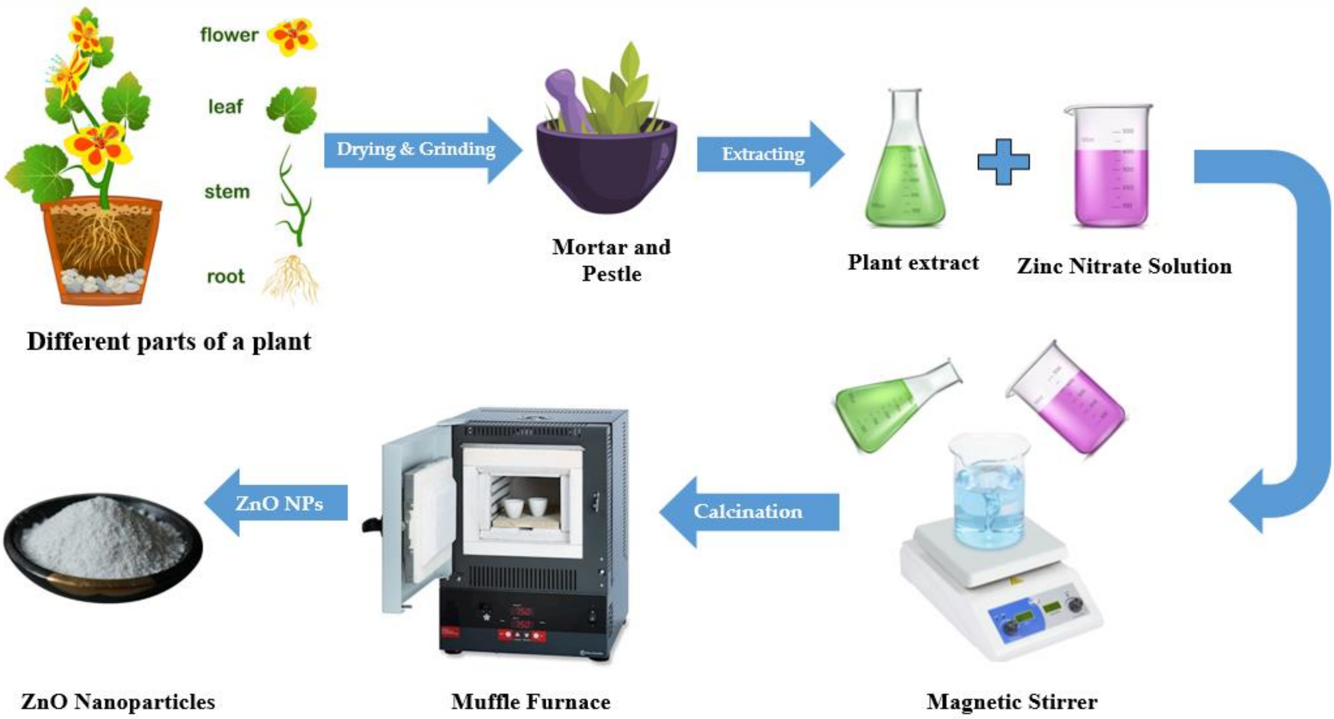

Figure 2. Green Synthesis Approach to ZnO Nanoparticles: A Step-by-Step Flow Chart

=Green synthesis of ZnO NPs utilizing Lupinus albus L. seed is studied by Teshiwal Bizuayen Adamu et al. for antibacterial and photocatalytic applications. ZnO NPs from Lupinus albus L. seed extract showed high photocatalytic activity. Antibacterial activity against Klebsiella pneumonia was highest with these seed extracts [72]. Green synthesis of ZnO NPs utilizing G. ulmifolia leaf demonstrated potential for use in biological applications.

XRD, UV-Vis, FTIR, SEM, and EDS were done for ZnO NPs characterization. The agar-well diffusion method was used for antibacterial property assessment. Antioxidant and antibacterial activities of ZnO NPs were demonstrated effectively [73]. Photocatalytic degradation of Congo red by Green synthesis of ZnO NPs using Epipremnum Aureum leaves was studied. XRD analysis confirmed the crystalline nature and hexagonal phase of nanoparticles. Also, The band gap of the particles was reported to be 3.73 eV. Under UV light, these ZnO NPs effectively degraded Congo red under the optimum conditions for CR degradation: pH 2, 10 ppm, 20 mg of catalyst [74].

Green synthesis of Ag2O doped ZnO NPs using Croton Macrostachyus leaf was studied. Nanoparticles exhibit nanorod-like morphology with sizes ranging between 16 to 23 nm. Synthesized nanoparticles exhibit enhanced photocatalytic and antioxidant properties. Doped nanoparticles degrade methylene blue dye efficiently under sunlight exposure [75]. M. Muthukathija et al. studied the Green synthesis of ZnO Nanoparticles utilizing Pisonia Alba leaf. It has been reported that Pisonia alba extract act as a capping and reducing agent. Green synthesized ZnO NPs had potent antibacterial properties against gram-positive and gram-negative bacteria [76]. Green synthesis of ZnO-NPs using mint and basil leaves was done to investigate physical properties, antibacterial potential, and plant uptake effects. XRD was done for chemical composition and phase purity confirmation. Green synthesis produced pure, crystalline ZnO-NPs with high purity. It was reported that mint and basil extracts enhanced Zn uptake and plant growth. Hence, ZnO-NPs improved wheat germination, varying growth based on species and concentrations [77]. Nanoparticle preparation using medicinal plants like Magnifera indica (Mango) seed was reported by Shanmugam Rajeshkumar et al. to study antibacterial and antioxidant activities. UV-Vis spectroscopy, FT-IR, XRD, SEM, TEM, and AFM techniques were used. Mango seed-wrapped ZnO NPs exhibit powerful antioxidant properties and inhibit bacterial growth efficiently, thereby showing significant antimicrobial potential [78].

Esraa Hamdy et al. reported that ZnO-NPs biosynthesized from E. japonica leaf extract showed insecticidal properties. Synthesized ZnO-NPs were effective against coleopteran pests and bacterial pathogens. Also, it was reported that antibacterial activity against potato pathogens was concentration-dependent. According to this study, ZnO-NPs can be used in pest management and potato diseases [79]. Michael Odoi Kyene reported ZnO NPs developed using root extract Cassia sieberiana exhibit good antioxidant activity and anti-microbial properties [80]. Shahid Awan et al. and Vidhya Selvanathan et al. had also studied plant-mediated ZnO-NPs for antibacterial and antioxidant activities. Shahid et al. used leaf extract of Ailanthus altissima for ZnO NPs synthesis. The ZnO Nanoparticles were having spherical shape with 13.27 nm average size. ZnO-NPs exhibited antioxidant efficiency with an IC50 value of 78.23 lg/mL. ZnO-NPs showed antibacterial activity. Vidhya Selvanathan et al. used Soursop leaf extract to synthesize ZnO NPs by microwave irradiation method. These nanoparticles also showed antibacterial activity [81, 82]. Amal Al-Mohaimeed et al. had reported Green synthesized ZnO nanoparticles from oat extract for biomedical applications. Antibacterial, antioxidant, and photocatalytic properties of ZnONPs were investigated. ZnONPs exhibited significant antioxidant effects with scavenging activity. ZnONPs showed antibacterial activity against various strains. Synthesized ZnO NPs showed photocatalytic potential for Rhodamine B dye degradation [83].

Hamad Sadiq et al. Synthesized ZnO NPs showed high photocatalytic activity and were capable of degrading MB dye effectively [84]. Lalitha Kolahalam et al. reported that Saussurea lappa root extract-based ZnO NPs showed antifungal, antibacterial activity, and cytotoxicity in opposition to CHO cells [85]. Shah Faisal et al. reported synthesis of ZnO Nanoparticles using Myristica fragrans showed antibacterial, antidiabetic, and antioxidant properties. also, reported ZnO NPs showed larvicidal action against Aedes aegypti and leishmanicidal activity. ZnO NPs had been capable of degrading methylene blue dye by 88% photocatalytically [86]. Raghavendra Sali et al. reported that biosynthesized ZnO and Ag-ZnO nanocomposites using Macrotyloma uniflorum leaf extract exhibit strong antibacterial activities against gram bacteria [87]. Rafael Álvarez-Chimal et al. stated that green synthesized ZnO-NPs the use of Dysphania ambrosioides plant extract also exhibited antibacterial residences towards numerous bacteria strains [88]. P. Ramesh et al. mentioned that ZnO NPs synthesized from Cassia auriculata leaf extract exhibited effective antibacterial residences, displaying antibacterial activity towards diverse pathogens [89].

Biogenic synthesis of ZnO NPs from Syzygium cumini leaves for dye toxicity removal was reported by Hamad Sadiq et al. Synthesized ZnO NPs showed high photocatalytic activity and were able to degrade MB dye effectively [84]. Lalitha Kolahalam et al. reported that Saussurea lappa root extract-based ZnO NPs showed antibacterial, antifungal activity, and cytotoxicity against CHO cells [85]. A study reported by Shah Faisal et al. reveals that green synthesis of ZnO-NPs from Myristica fragrans showed antibacterial, antidiabetic, and antioxidant properties. Also, reported ZnO-NPs showed larvicidal activity against Aedes aegypti and leishmanicidal activity. ZnO-NPs were able to degrade methylene blue dye by 88% photocatalytically [86]. Raghavendra Sali et al. reported that biosynthesized ZnO and Ag-ZnO nanocomposites using Macrotyloma uniflorum leaf extract exhibit strong antibacterial activities against gram bacteria [87]. Rafael Álvarez-Chimal et al. reported that green synthesized ZnO-NPs using Dysphania ambrosioides plant extract also demonstrated antibacterial properties against different bacteria strains [88]. According to P. Ramesh et al., ZnO nanoparticles synthesized using Cassia auriculata leaf extract have strong antibacterial properties and exhibit antibacterial activity against various pathogens [89].

Fatemeh Norouzi et al. studied the green synthesis of ZnO NPs using Amygdalus scoparia for antimicrobial, anticancer, and antidiabetic properties. ZnO NPs showed potential as a remedial agent for various conditions. Also, enhance insulin levels and reduce blood glucose levels, AST, ALT, and improved gene expression. ZnO NPs biosynthesized from A. scoparia showed remarkable inhibitory activity by inhibiting bacteria, fungi, cancer, and diabetes effectively [90]. Sunday Wilson Balogun et al. studied synthesis of ZnO NPs utilizing Mimosa pudica extract and their energy applications. Synthesized ZnO NPs thin film absorbs light from 235 to 300 nm. ZnO NPs thin film device has 0.7% efficiency under illumination for solar cells [91]. Wali Muhammad et al. synthesized ZnO NPs from Papaver somniferum L. for theranostic applications. ZnO NPs from Papaver somniferum demonstrated anti-diabetic activity, biocompatibility, and bactericidal properties. ZnO NPs are biocompatible with RBCs and effective against drug-resistant bacteria. They showed moderate enzyme inhibition and no RBC damage. These particles had potential for theranostic applications in drug delivery [92]. Harish Chandra et al. also reported synthesis of ZnO NPs using leaf extract of Berberis aristata, which also shows antibacterial activity and exhibits moderate antioxidant potential [93].

Table 1 : The green synthesis of ZnO-NPs reported in recent literature :

Year	Plant Name	Part of the plant	Shape	Size [nm]	Characterization Techniques	Applications	Ref.
2024	Spinacia oleracea	leaf	Spherical	35-40	XRD,SEM,TEM,UV	Photocatalytic activity	[67]

2024	Sorghum bicolor	Seed	Spherical & Hemi-spherical	11-15	XRD,SEM, UV, FTIR	Photocatalytic activity	[68]
2024	Sorghum Panicle	Panicle	Spherical	59	XRD , UV, FTIR FESEM,EDS, TGA/DTA	Photocatalytic activity, Antibacterial activity, Phytotoxicity	[69]
2024	Citrus sinensis [Orange]	Peels	Irregular	36	XRD , UV, FTIR, SEM,EDS	Photocatalytic activity	[70]
2024	Nauclea latifolia	Fruit	Spherical to Hexagonal	14	XRD, SEM, TEM, UV, FTIR, BET, TGA/DTA	Photocatalytic activity	[71]
2024	Lupinus albus L. [white lupin]	Seed	Spherical	20-30	XRD, SEM, UV, FTIR, TGA/DTA	Photocatalytic activity	[72]
2024	Guazuma ulmifolia	leaf	Spherical	27	XRD , UV, FTIR SEM,EDX	Antioxidant activity, Antimicrobial activity	[73]
2024	Epipremnum aureum	leaf	Spherical	19	XRD, SEM, , UV, FTIR,EDX, TGA/DTA	Photocatalytic activity	[74]
2024	Croton macrostachyus	leaf	Rod-like	16-23	XRD, SAED, UV, HRTEM, TEM, SEM, FTIR, EDX	Photocatalytic activity, Antioxidant activity	[75]
2023	Pisonia Alba	leaf	Rod-like	48	XRD, SEM, , UV, FTIR,EDX	Antibacterial activity	[76]
2023	Mentha spicata	leaf	Triangular	94	XRD, SEM, , UV, FTIR	Antibacterial activity	[77]
2023	Mangifera indica	Seed	Spherical	40-60	SEM, EDX, AFM, XRD, FTIR	Antibacterial activity, Antioxidant activity	[78]
2023	Eriobotrya japonica	leaf	Irregular & Spherical	5-27	XRD, SEM, , UV, FTIR, DLS	Antibacterial activity	[79]
2023	Cassia sieberiana	Root	Spherical	10-16	XRD, SEM, TEM, UV, FTIR, EDX	Anti-inflammatory, Antioxidant and antimicrobial activities	[80]
2023	Ailanthus altissima	leaf	Spherical	13	XRD, UV, SEM, FTIR	Antibacterial activity, Antioxidant activity	[81]
2022	Annona muricata L	leaf	Quasi-spherical	37	XRD, FESEM,TEM, FTIR , UV, Raman	Antibacterial activity	[82]
2022	Avena Sativa [Oat]	Seeds	Hexagonal	17.5	XRD, SEM, TEM, UV, EDX, FTIR, TGA/DSC	Antibacterial activity, Photocatalytic activity, Antioxidant activity	[83]
2021	Syzygium Cumini	leaf	Agglomera-ted structure	11.35	XRD, FTIR, SEM, UV, , EDX,	Photocatalytic activity	[84]
2021	Saussurea lappa	Root	Hexagonal	26	XRD, FESEM FTIR , UV	Antimicrobial activity, Cytotoxic activity	[85]
2021	Myristica fragrans	Fruit	Elliptical shape	66	XRD, SEM, TEM, UV, FTIR, EDX, TGA, DLS	Antioxidant activity, Photocatalytic activity	[86]
2021	Macrotyloma Uniflorum	Leaf	Hexagonal	128	XRD, SEM, TEM, UV, FTIR, EDX, DLS	Antibacterial activity	[87]
2021	Dysphania ambrosioides	Leaf	Quasi-spherical	5-30	FESEM, TEM, EDS, HRTEM, XRD, FTIR and TGA	Antibacterial activity	[88]
2021	Cassia auriculata	Leaf	Nano Rod & Nano Flower	20-30	XRD, FESEM, UV, FTIR, TEM, EDX	Antibacterial activity	[89]
2021	Amygdalus scoparia	Stem Bark	Spherical	15-40	TEM, EDX, FESEM, UV	Antibacterial activity, Antifungal activity, Anticancer activity, Anti-diabetic agent	[90]
2020	Mimosa pudica	Leaf	Spherical	15	XRD, UV, SEM, FTIR	Photoanode in Dye sensitized solar cells	[91]
2019	Papaver somniferum L.	Pod	Spherical	48	XRD, TEM, SEM, FTIR, UV,	Antibacterial activity, Antidiabetic activity	[92]
2019	Berberis aristata	Leaf	Needle like	20-40	XRD, SEM, UV, FTIR, EDX, DLS	Antibacterial activity, Antioxidant activity	[93]

4. Conclusion

Recent advances in the synthesis of ZnO nanoparticles using various plant extracts has meticulously explored, focusing on the characterization and diverse applications of ZnO nanoparticles. The green synthesis technique provides a promising alternative approach of synthesis of ZnO nanoparticles. This method not only reduces the environmental and health hazards associated with traditional synthesis techniques but also promotes the use of renewable resources and reducing waste generation. Future prospects for the environmentally friendly manufacturing of ZnO nanoparticles utilizing extracts of different plants are extremely promising. During the synthesis of nanoparticles, a substantial and mainly unexplored pool of bioactive compounds found in plants can serve as stabilising and reducing agents. This not only makes the process more environmentally friendly, but it also makes it possible to create nanoparticles with certain qualities that are suited for particular uses.Furthermore, the exploration of a broader range of plant species, including those from underutilized or indigenous flora, could unlock new possibilities in nanoparticle synthesis. This approach not only promotes biodiversity but also supports sustainable development by utilizing locally available resources, particularly in regions rich in plant diversity. Future research could focus on optimizing extraction methods, understanding the role of specific phytochemicals in nanoparticle formation, and scaling up the synthesis process for industrial applications.

References

[1] L. A. Kolahalam, I. V. Kasi Viswanath, B. S. Diwakar, B. Govindh, V. Reddy, and Y. L. N. Murthy, "Review on nanomaterials: Synthesis and applications," *Mater Today Proc*, vol. 18, pp.**2182–2190, 2019.** https://doi.org/10.1016/J.MATPR.2019.07.371

[2] P. G. Jamkhande, N. W. Ghule, A. H. Bamer, and M. G. Kalaskar, "Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications," *J Drug Deliv Sci Technol*, vol. 53, p.101174, **2019**. https://doi.org/10.1016/J.JDDST.2019.101174

[3] D. Titus, E. James Jebaseelan Samuel, and S. M. Roopan, "Nanoparticle characterization techniques," *Green Synthesis, Characterization and Applications of Nanoparticles*, pp.**303–319, 2019.** https://doi.org/10.1016/B978-0-08-102579-6.00012-5

[4] J.-H. Li, H.-Y. Zhang, Q.-W. Shi, J. Ying, and C. Janiak, "Encapsulated Pt-based nanoparticles for catalysis," *Prog Mater Sci*, vol. 146, p. 101335, **2024**. https://doi.org/10.1016/j.pmatsci.2024.101335

[5] P. Kumari, K. P. Misra, S. Chattopadhyay, and S. Samanta, "A brief review on transition metal ion doped ZnO nanoparticles and its optoelectronic applications," *Mater Today Proc*, Vol.**43**, pp.**3297–3302, 2021.** https://doi.org/10.1016/j.matpr.2021.02.299

[6] T. Mwebembezi, J. Wakatuntu, J. Jjagwe, C. Kanyesigye, R. N. Kulabako, and P. W. Olupot, "Synthesis, characterization and application of steel waste-based iron oxide nanoparticles for removal of heavy metals from industrial wastewaters," *Heliyon*, Vol.**10**, No.6, p. e28153, **2024.** https://doi.org/10.1016/j.heliyon.2024.e28153

[7] M. Alavi, P. Kamarasu, D. J. McClements, and M. D. Moore, "Metal and metal oxide-based antiviral nanoparticles: Properties, mechanisms of action, and applications," *Adv Colloid Interface Sci*, vol. 306, p. 102726, **2022**. https://doi.org/10.1016/j.cis.2022.102726

[8] R. H. Althomali and W. A. Adeosun, "Wet chemically synthesized metal oxides nanoparticles, characterization and application in electrochemical energy storage: An updated review," *Synth Met*, vol. 298, p. 117424, **2023**. https://doi.org/10.1016/j.synthmet.2023.117424

[9] T. Shahraki, M. R. Naroui Rad, H. R. Ganjali, H. Kamaladini, and H. R. Mobaser, "Metallic and metal oxide nanoparticles synthesized from melon juice. Synthesis, biological application, antioxidant, anticancer, and green catalyst in p-nitrophenol reduction," *Inorg Chem Commun*, vol. 158, p. 111636, Dec. **2023**. https://doi.org/10.1016/j.inoche.2023.111636

[10] H. F. Etefa, D. J. Nemera, K. T. Etefa, and E. R. Kumar, "Evaluation of physicochemical properties of zinc oxide and indium-tin oxide nanoparticles for photocatalysis and biomedical activities," *Current Applied Physics*, vol. 67, pp.**133–142, 2024.** https://doi.org/10.1016/j.cap.2024.08.001

[11] B. H. J. Gowda *et al.*, "Current trends in bio-waste mediated metal/metal oxide nanoparticles for drug delivery," *J Drug Deliv Sci Technol*, vol. 71, p. 103305, May **2022**. https://doi.org/10.1016/j.jddst.2022.103305

[12] F. Séby, "Metal and metal oxide nanoparticles in cosmetics and skin care products," pp.**381–427, 2021.** https://doi.org/10.1016/bs.coac.2021.02.009

[13] R. Nayal, D. Mejjo, and M. Y. Abajy, "Anti inflammatory properties and safety of green synthesized metal and metal oxide nanoparticles: A review article," *European Journal of Medicinal Chemistry Reports*, vol. 11, p. 100169, Aug. **2024**. https://doi.org/10.1016/j.ejmcr.2024.100169

[14] L. Dyshlyuk, O. Babich, S. Ivanova, N. Vasilchenco, A. Prosekov, and S. Sukhikh, "Suspensions of metal nanoparticles as a basis for protection of internal surfaces of building structures from biodegradation," *Case Studies in Construction Materials*, vol. 12, p. e00319, Jun. **2020**. https://doi.org/10.1016/j.cscm.2019.e00319

[15] A. Khorsand Zak and A. M. Hashim, "Optical properties and band-gap engineering of group (I) element-doped ZnO nanoparticles as P-type semiconductors," *Opt Mater (Amst)*, vol.**152**, p. 115434, Jun. **2024**. https://doi.org/10.1016/j.optmat.2024.115434

[16] V. N. Hegde, M. V. V, P. T. M, and H. B. C, "Study on structural, morphological, elastic and electrical properties of ZnO nanoparticles for electronic device applications," *Journal of Science: Advanced Materials and Devices*, vol. 9, no. 3, p. 100733, Sep. **2024**. https://doi.org/10.1016/j.jsamd.2024.100733

[17] V. P. Klienchen de Maria *et al.*, "Advances in ZnO nanoparticles in building material: Antimicrobial and photocatalytic applications – Systematic literature review," *Constr Build Mater*, vol.417, p. 135337, Feb. **2024**. https://doi.org/10.1016/j.conbuildmat.2024.135337

[18] I V. Ferreira, N. R. Neng, O. C. Monteiro, and V. C. Ferreira, "Immobilisation of ZnO nanoparticles on carbon and on glass fibres for visible light photocatalytic applications," *J Photochem Photobiol A Chem*, vol. 453, p. 115653, Aug. **2024**. https://doi.org/10.1016/j.jphotochem.2024.115653

[19] Y. Y. Chan, Y. L. Pang, S. Lim, and W. C. Chong, "Facile green synthesis of ZnO nanoparticles using natural-based materials: Properties, mechanism, surface modification and application," *J Environ Chem Eng*, Vol.**9**, No.**4**, p.105417, **2021**. https://doi.org/10.1016/j.jece.2021.105417

[20] M. Naseer, U. Aslam, B. Khalid, and B. Chen, "Green route to synthesize Zinc Oxide Nanoparticles using leaf extracts of Cassia fistula and Melia azadarach and their antibacterial potential," *Sci Rep*, vol. 10, no. 1, p. 9055, Jun. **2020**. https://doi.org/10.1038/s41598-020-65949-3

[21] S. Iravani, "Green synthesis of metal nanoparticles using plants," *Green Chemistry*, vol. 13, no. 10, p. 2638, **2011**. https://doi.org/10.1039/c1gc15386b

[22] P. Kumar and R. Kumar, "Synthesis process of functionalized ZnO nanostructure for additive manufacturing: a state-of-the-art review," in *Additive Manufacturing with Functionalized Nanomaterials*, Elsevier, pp.**135–153, 2021.** https://doi.org/10.1016/B978-0-12-823152-4.00002-8

[23] Z. Zhang and G. Wen, "Synthesis and characterization of carbon-encapsulated magnetite, martensite and iron nanoparticles by high-energy ball milling method," *Mater Charact*, vol. 167, p. 110502, Sep. **2020**. https://doi.org/10.1016/j.matchar.2020.110502

[24] S. Benchelia, Y. Messai, A. Chetoui, and D. E. Mekki, "Enhancing antibacterial activity through controlled ball milling: Structural, morphological and optical studies of ZnO nanoparticles," *Nano-Structures & Nano-Objects*, vol. 39, p. 101285, Sep. **2024**. https://doi.org/10.1016/j.nanoso.2024.101285

[25] S. Wirunchit, P. Gansa, and W. Koetniyom, "Synthesis of ZnO nanoparticles by Ball-milling process for biological applications," *Mater Today Proc*, Vol.**47**, pp.**3554–3559, 2021.** https://doi.org/10.1016/j.matpr.2021.03.559

[26] C. M. Montemayor Palos *et al.*, "Large-scale production of ZnO nanoparticles by high energy ball milling," *Physica B Condens Matter*, vol. 656, p. 414776, May **2023**. https://doi.org/10.1016/j.physb.2023.414776

[27] Y. Fang, Y. Wang, Y. Wan, Z. Wang, and J. Sha, "Detailed Study on Photoluminescence Property and Growth Mechanism of ZnO Nanowire Arrays Grown by Thermal Evaporation," *The Journal of Physical Chemistry C*, Vol.**114**, No.**29**, pp.**12469–12476, 2010.** https://doi.org/10.1021/jp103711m

[28] N. Hamid, S. Suhaimi, M. Z. Othman, and W. Z. W. Ismail, "A Review on Thermal Evaporation Method to Synthesis Zinc Oxide as Photocatalytic Material," *Nano Hybrids and Composites*, Vol.**31**, pp.**55–63**, **2021.** https://doi.org/10.4028/www.scientific.net/NHC.31.55

[29] M. Rashad, N. M. Shaalan, and A. M. Abd-Elnaiem, "Degradation enhancement of methylene blue on ZnO nanocombs synthesized by thermal evaporation technique," *Desalination Water Treat*, Vol.**57**, No.**54**, pp.**26267–26273, 2016.** https://doi.org/10.1080/19443994.2016.1163511

[30] F. H. Alsultany, Z. Hassan, and N. M. Ahmed, "Control growth of catalyst-free ZnO tetrapods on glass substrate by thermal evaporation method," *Ceram Int*, vol. 42, no. 11, pp. 13144–13150, Aug. **2016** https://doi.org/10.1016/j.ceramint.2016.05.102

[31] R. Godiwal *et al.*, "Synthesis and growth mechanism of ZnO nanocandles using thermal evaporation and their efficient CO sensing performance," *Micro and Nanostructures*, vol. 184, p. 207692, Dec. 2023. https://doi.org/10.1016/j.micrna.2023.207692

[32] A O. Dikovska, M. T. Alexandrov, G. B. Atanasova, N. T. Tsankov, and P. K. Stefanov, "Silver nanoparticles produced by PLD in vacuum: role of the laser wavelength used," *Applied Physics A*, vol. 113, no. 1, pp. 83–88, Oct. **2013** https://doi.org/10.1007/s00339-013-7834-9

[33] M. Hirasawa, T. Orii, and T. Seto, "Effect of insitu annealing on physical properties of Si nanoparticles synthesized by pulsed laser ablation," *Applied Physics A*, vol. 79, no. 4–6, pp. 1421–1424, Sep. 2004. https://doi.org/10.1007/s00339-004-2800-1

[34] A O. El-Gendy *et al.*, "Preparation of zinc oxide nanoparticles using laser-ablation technique: Retinal epithelial cell (ARPE-19) biocompatibility and antimicrobial activity when activated with femtosecond laser," *J Photochem Photobiol B*, vol. 234, p. 112540, Sep. 2022. https://doi.org/10.1016/j.jphotobiol.2022.112540

[35] D. Bokov *et al.*, "Nanomaterial by Sol-Gel Method: Synthesis and Application," *Advances in Materials Science and Engineering*, vol. 2021, no. 1, Jan. 2021. https://doi.org/10.1155/2021/5102014

[36] Z. Wang, L. Shi, F. Wu, S. Yuan, Y. Zhao, and M. Zhang, "The sol–gel template synthesis of porous TiO_2 for a high performance humidity sensor," *Nanotechnology*, vol. 22, no. 27, p. 275502, Jul. 2011. https://doi.org/10.1088/0957-4484/22/27/275502

[37] S. Gupta and M. Tripathi, "A review on the synthesis of TiO2 nanoparticles by solution route," *Open Chem*, vol. 10, no. 2, pp. 279–294, Apr. 2012. https://doi.org/10.2478/s11532-011-0155-y

[38] J. N. Hasnidawani, H. N. Azlina, H. Norita, N. N. Bonnia, S. Ratim, and E. S. Ali, "Synthesis of ZnO Nanostructures Using Sol-Gel Method," *Procedia Chem*, vol. 19, pp. 211–216, 2016. https://doi.org/10.1016/j.proche.2016.03.095

[39] K. Al Abdullah, S. Awad, J. Zaraket, and C. Salame, "Synthesis of ZnO Nanopowders By Using Sol-Gel and Studying Their Structural and Electrical Properties at Different Temperature," *Energy Procedia*, vol. 119, pp. 565–570, Jul. 2017. https://doi.org/10.1016/j.egypro.2017.07.080

[40] M. F. Khan *et al.*, "Sol-gel synthesis of thorn-like ZnO nanoparticles endorsing mechanical stirring effect and their antimicrobial activities: Potential role as nano-antibiotics," *Sci Rep*, vol. 6, no. 1, p. 27689, Jun. 2016. https://doi.org/10.1038/srep27689

[41] I Ben Amor, H. Hemmami, S. E. Laouini, M. S. Mahboub, and A. Barhoum, "Sol-Gel Synthesis of ZnO Nanoparticles Using Different Chitosan Sources: Effects on Antibacterial Activity and Photocatalytic Degradation of AZO Dye," *Catalysts*, vol. 12, no. 12, p. 1611, Dec. **2022**. https://doi.org/10.3390/catal12121611

[42] C. Li *et al.*, "Chemical Precipitation Method for the Synthesis of Nb₂O₅ Modified Bulk Nickel Catalysts with High Specific Surface Area," *Journal of Visualized Experiments*, no. 132, Feb. **2018**. https://doi.org/10.3791/56987

[43] M. A. Gatou, N. Lagopati, I.-A. Vagena, M. Gazouli, and E. A. Pavlatou, "ZnO Nanoparticles from Different Precursors and Their Photocatalytic Potential for Biomedical Use," *Nanomaterials*, vol. 13, no. 1, p. 122, Dec. 2022. https://doi.org/10.3390/nano13010122

[44] M. A. Gatou *et al.*, "Optimization of ZnO Nanoparticles' Synthesis via Precipitation Method Applying Taguchi Robust Design," *Catalysts*, Vol.**13**, No.**10**, p. 1367, **2023**. https://doi.org/10.3390/catal13101367

[45] Y. X. Gan, A. H. Jayatissa, Z. Yu, X. Chen, and M. Li, "Hydrothermal Synthesis of Nanomaterials," *J Nanomater*, Vol.**2020**, pp.**1–3, 2020.** https://doi.org/10.1155/2020/8917013

[46] N. K. V. Nadimpalli, R. Bandyopadhyaya, and V. Runkana, "Thermodynamic analysis of hydrothermal synthesis of nanoparticles," *Fluid Phase Equilib*, Vol.**456**, pp.**33–45, 2018.** https://doi.org/10.1016/j.fluid.2017.10.002

[47] S. Mohan, M. Vellakkat, A. Aravind, and R. U, "Hydrothermal synthesis and characterization of Zinc Oxide nanoparticles of various shapes under different reaction conditions," *Nano Express*, Vol.1, No.3, p.030028, **2020.** https://doi.org/10.1088/2632-959X/abc813

[48] D. B. Bharti and A. V. Bharati, "Synthesis of ZnO nanoparticles using a hydrothermal method and a study its optical activity," *Luminescence*, Vol.**32**, No.**3**, pp.**317–320, 2017.** https://doi.org/10.1002/bio.3180

[49] M. Søndergaard, E. D. Bøjesen, M. Christensen, and B. B. Iversen, "Size and Morphology Dependence of ZnO Nanoparticles Synthesized by a Fast Continuous Flow Hydrothermal Method," *Cryst Growth Des*, Vol.**11**, No.**9**, pp.**4027–4033, 2011.** https://doi.org/10.1021/cg200596c

[50] U. S. Mohanty, "Electrodeposition: a versatile and inexpensive tool for the synthesis of nanoparticles, nanorods, nanowires, and nanoclusters of metals," *J Appl Electrochem*, Vol.**41**, No.**3**, pp.**257–270, 2011.** https://doi.org/10.1007/s10800-010-0234-3

[51] J. Ustarroz, X. Ke, A. Hubin, S. Bals, and H. Terryn, "New Insights into the Early Stages of Nanoparticle Electrodeposition," *The Journal of Physical Chemistry C*, Vol.**116**, No.3, pp.**2322–2329, 2012.** https://doi.org/10.1021/jp210276z

[52] L. Xu, Q. Chen, and D. Xu, "Hierarchical ZnO Nanostructures Obtained by Electrodeposition," *The Journal of Physical Chemistry C*, Vol.**111**, No.**31**, pp.**11560–11565, 2007.** https://doi.org/10.1021/jp071536a

[53] H. Usui, "Electrochemical self-assembly synthesis of zinc oxide nanoparticles and lamellar-structured organic/inorganic hybrids by electrodeposition in surfactant solution," *Electrochim Acta*, vol. 56, no. 11, pp. 3934–3940, Apr. **2011**. https://doi.org/10.1016/j.electacta.2011.02.023

[54] G. Jiangfeng, D. Zhaoming, D. Qingping, X. Yuan, and Z. Weihua, "Controlled Synthesis of ZnO Nanostructures by Electrodeposition Method," *J Nanomater*, vol. 2010, no. 1, Jan. **2010**. https://doi.org/10.1155/2010/740628

[55] B. Patella *et al.*, "Electrochemical Synthesis of Zinc Oxide Nanostructures on Flexible Substrate and Application as an Electrochemical Immunoglobulin-G Immunosensor," *Materials*, vol. 15, no. 3, p. 713, Jan. **2022**. https://doi.org/10.3390/ma15030713

[56] P. Piszczek and A. Radtke, "Silver Nanoparticles Fabricated Using Chemical Vapor Deposition and Atomic Layer Deposition Techniques: Properties, Applications and Perspectives: Review," in *Noble and Precious Metals - Properties, Nanoscale Effects and Applications*, InTech, **2018**. https://doi.org/10.5772/intechopen.71571

[57] F. Jia, Y.-L. Shih, D. Y. H. Pui, Z.-Y. Li, and C.-J. Tsai, "Generation of ZnO nanoparticles by chemical vapor synthesis

using quenching air," *Journal of Nanoparticle Research*, vol. 23, no. 2, p. 58, **2021.** https://doi.org/10.1007/s11051-021-05145-0

[58] R. Müller *et al.*, "Chemical Vapor Deposition Growth of Zinc Oxide on Sapphire with Methane: Initial Crystal Formation Process," *Cryst Growth Des*, Vol.**19**, No.**9**, pp.**4964–4969, 2019.** https://doi.org/10.1021/acs.cgd.9b00181

[59] P.-C. Chang *et al.*, "ZnO Nanowires Synthesized by Vapor Trapping CVD Method," *Chemistry of Materials*, vol.**16**, No.**24**, pp.**5133–5137**, **2004**. https://doi.org/10.1021/cm049182c

[60] S. Saif, A. Tahir, and Y. Chen, "Green Synthesis of Iron Nanoparticles and Their Environmental Applications and Implications," *Nanomaterials*, Vol.**6**, No.**11**, p.209, **2016.** https://doi.org/10.3390/nano6110209

[61] S. Ying *et al.*, "Green synthesis of nanoparticles: Current developments and limitations," *Environ Technol Innov*, vol.**26**, p. 102336, May **2022**. https://doi.org/10.1016/j.eti.2022.102336

[62] N. Kulkarni and U. Muddapur, "Biosynthesis of Metal Nanoparticles: A Review," *J Nanotechnol*, vol. 2014, pp.**1–8, 2014.** https://doi.org/10.1155/2014/510246

[63] V. V. Makarov et al., "'Green' Nanotechnologies: Synthesis of Metal Nanoparticles Using Plants," Acta Naturae, Vol.6, no.**1**, pp.**35–44**, **2014**, https://doi.org/10.32607/20758251-2014-6-1-35-44

[64] G. Kavitha, J. V. Kumar, R. Arulmozhi, and N. Abirami, "Green synthesis of Copper Oxide Nanoparticles Decorated with Graphene oxide for Anticancer Activity and Catalytic Applications: An Advanced Study Approach," in *New Innovations in Chemistry and Biochemistry Vol. 6*, Book Publisher International (a part of SCIENCEDOMAIN International), pp.**124–142, 2021.** https://doi.org/10.9734/bpi/nicb/v6/1660B

[65] M. Pradeep, D. Kruszka, P. Kachlicki, D. Mondal, and G. Franklin, "Uncovering the Phytochemical Basis and the Mechanism of Plant Extract-Mediated Eco-Friendly Synthesis of Silver Nanoparticles Using Ultra-Performance Liquid Chromatography Coupled with a Photodiode Array and High-Resolution Mass Spectrometry," *ACS Sustain Chem Eng*, vol. 10, no. 1, pp. 562–571, Jan. **2022**. https://doi.org/10.1021/acssuschemeng.1c06960

[66] U. O. Aigbe and O. A. Osibote, "Green synthesis of metal oxide nanoparticles, and their various applications," Feb. 01, 2024, *Elsevier B.V.* https://doi.org/10.1016/j.hazadv.2024.100401

[67] V. G, J. S. Chohan, P. Paramasivam, R. Maranan, and N. M, "Green marvel: Harnessing spinach leaves' power for enhanced photodegradation of various effluents with biogenic ZnO nanoparticles," *Desalination Water Treat*, vol. 319, p. 100566, Jul. **2024**. https://doi.org/10.1016/j.dwt.2024.100566

[68] M. E. Cervantes-Gaxiola, F. A. Vázquez-González, E. Y. Rios-Iribe, P. F. Méndez-Herrera, and C. Leyva, "Effect of pH on the green synthesis of ZnO nanoparticles using Sorghum bicolor seed extract and their application in photocatalytic dye degradation," *Mater Lett*, vol. 372, p. 136982, Oct. **2024**. https://doi.org/10.1016/j.matlet.2024.136982

[69] N. J. Lakshmi, S. Anandakumar, V. Sampathkumar, and S. Manoj, "Synthesized ZnO nanoparticles using Sorghum Panicle for the photocatalytic degradation of pharmaceutical waste water," *Desalination Water Treat*, vol. 319, p. 100557, Jul. **2024**. https://doi.org/10.1016/j.dwt.2024.100557

[70] A K. M. A. Habib, K. M. R. Rifat, M. E. Kabir, J. N. Khan, S. M. N. Rokon, and M. A. Rabbi, "Improved photocatalytic activity of (Ni, Mn) co-doped ZnO nanoparticles prepared via green synthesis route using orange peel extract," *Results in Materials*, vol. 22, p. 100581, Jun. **2024**. https://doi.org/10.1016/j.rinma.2024.100581

[71] S. M. Abegunde, M. A. Adebayo, and E. F. Olasehinde, "Green synthesis of ZnO nanoparticles and its application for methyl green dye adsorption," *Green Energy and Resources*, vol. 2, no. 2, p. 100073, Jun. **2024**. https://doi.org/10.1016/j.gerr.2024.100073

[72] T. Bizuayen Adamu, A. Melese Mengesha, M. Assefa Kebede, B. Lake Bogale, and T. Walle Kassa, "Facile biosynthesis of zinc oxide nanoparticles (ZnO NPs) using Lupinus albus L (Gibto) seed extract for antibacterial and photocatalytic applications," *Results Chem*, vol. 10, p. 101724, Aug. **2024**. https://doi.org/10.1016/j.rechem.2024.101724

[73] S. E. Dafalla *et al.*, "Green and sustainable synthesis of the ZnONPs using leaf extract of Guazuma ulmifolia for antioxidant and antimicrobial activities," *Journal of Umm Al-Qura University for Applied Sciences*, **2024**. https://doi.org/10.1007/s43994-024-00161-x

[74] R. S. Brishti *et al.*, "Green synthesis of ZnO NPs using aqueous extract of Epipremnum aureum leave: Photocatalytic degradation of Congo red," *Results Chem*, vol.7, p. 101441, **2024.** https://doi.org/10.1016/j.rechem.2024.101441

[75] T. J. Masho, P. T. Arasu, R. F. Bogale, and K. M. Gendo, "Green synthesis, characterization of Ag2O doped ZnO nanoparticles using aqueous extract of Croton macrostachyus leaf for photo degradation, and antioxidant activities," *Results Chem*, vol. 7, p. 101478, Jan. **2024**. https://doi.org/10.1016/j.rechem.2024.101478

[76] M. MuthuKathija, M. Sheik Muhideen Badhusha, and V. Rama, "Green synthesis of zinc oxide nanoparticles using Pisonia Alba leaf extract and its antibacterial activity," *Applied Surface Science Advances*, vol. 15, p. 100400, Jun. **2023**. https://doi.org/10.1016/j.apsadv.2023.100400

[77] Z. Görkem Doğaroğlu, Y. Uysal, Z. Çaylalı, and D. Sefkan Karakulak, "Environmental Science and Pollution Research on April 11th, 2023. See the published version," **2023**. https://doi.org/10.21203/rs.3.rs-2546585/v1

[78] S. Rajeshkumar, R. P. Parameswari, D. Sandhiya, K. A. Al-Ghanim, M. Nicoletti, and M. Govindarajan, "Green Synthesis, Characterization and Bioactivity of Mangifera indica Seed-Wrapped Zinc Oxide Nanoparticles," *Molecules*, vol. 28, no. 6, p. 2818, Mar. **2023**. https://doi.org/10.3390/molecules28062818

[79] E. Hamdy *et al.*, "Zinc Oxide Nanoparticles Biosynthesized by Eriobotrya japonica Leaf Extract: Characterization, Insecticidal and Antibacterial Properties," *Plants*, vol. 12, no. 15, p. 2826, Jul. **2023**. https://doi.org/10.3390/plants12152826

[80] M. O. Kyene *et al.*, "Synthesis and characterization of ZnO nanomaterial from Cassia sieberiana and determination of its anti-inflammatory, antioxidant and antimicrobial activities," *Sci Afr*, vol. 19, p. e01452, Mar. **2023**. https://doi.org/10.1016/j.sciaf.2022.e01452

[81] S. Shabbir Awan *et al.*, "Ailanthus altissima leaf extract mediated green production of zinc oxide (ZnO) nanoparticles for antibacterial and antioxidant activity," *Saudi J Biol Sci*, vol. 30, no. 1, p. 103487, Jan. **2023**. https://doi.org/10.1016/j.sjbs.2022.103487

[82] V. Selvanathan *et al.*, "Synthesis, characterization, and preliminary in vitro antibacterial evaluation of ZnO nanoparticles derived from soursop (Annona muricata L.) leaf extract as a green reducing agent," *Journal of Materials Research and Technology*, vol. 20, pp. 2931–2941, Sep. **2022**. https://doi.org/10.1016/j.jmrt.2022.08.028

[83] A. M. Al-Mohaimeed, W. A. Al-Onazi, and M. F. El-Tohamy, "Multifunctional Eco-Friendly Synthesis of ZnO Nanoparticles in Biomedical Applications," *Molecules*, vol. 27, no. 2, p. 579, Jan. **2022**. https://doi.org/10.3390/molecules27020579

[84] H. Sadiq *et al.*, "Green synthesis of ZnO nanoparticles from Syzygium Cumini leaves extract with robust photocatalysis applications," *J Mol Liq*, vol. 335, p. 116567, Aug. **2021**. https://doi.org/10.1016/j.molliq.2021.116567

[85] L. A. Kolahalam, K. R. S. Prasad, P. Murali Krishna, and N. Supraja, "Saussurea lappa plant rhizome extract-based zinc oxide nanoparticles: synthesis, characterization and its antibacterial, antifungal activities and cytotoxic studies against Chinese Hamster Ovary (CHO) cell lines," *Heliyon*, Vol.**7**, No.**6**, p. e07265, Jun. **2021**. https://doi.org/10.1016/j.heliyon.2021.e07265

[86] S. Faisal *et al.*, "Green Synthesis of Zinc Oxide (ZnO) Nanoparticles Using Aqueous Fruit Extracts of *Myristica fragrans* : Their Characterizations and Biological and Environmental Applications," *ACS Omega*, Vol.**6**, No.**14**, pp.**9709–9722, 2021.** https://doi.org/10.1021/acsomega.1c00310

[87] R. K. Sali, M. S. Pujar, S. Patil, and A. H. Sidarai, "Green Synthesis of ZnO and Ag-ZnO Nanoparticles using Macrotyloma Uniflorum: Evaluation of Antibacterial Activity."

[88] R. Álvarez-Chimal, V. I. García-Pérez, M. A. Álvarez-Pérez, and J. Á. Arenas-Alatorre, "Green synthesis of ZnO nanoparticles using a Dysphania ambrosioides extract. Structural characterization and

antibacterial properties," *Materials Science and Engineering: C*, vol. 118, p. 111540, **2021.** https://doi.org/10.1016/j.msec.2020.111540

[89] P. Ramesh, K. Saravanan, P. Manogar, J. Johnson, E. Vinoth, and M. Mayakannan, "Green synthesis and characterization of biocompatible zinc oxide nanoparticles and evaluation of its antibacterial potential," *Sens Biosensing Res*, Vol.**31**, p. 100399, **2021**. https://doi.org/10.1016/j.sbsr.2021.100399

[90] F. Norouzi Jobie, M. Ranjbar, A. Hajizadeh Moghaddam, and M. Kiani, "Green synthesis of zinc oxide nanoparticles using Amygdalus scoparia Spach stem bark extract and their applications as an alternative antimicrobial, anticancer, and anti-diabetic agent," *Advanced Powder Technology*, vol.**32**, No.**6**, pp.**2043–2052, 2021.** https://doi.org/10.1016/j.apt.2021.04.014

[91] S. W. Balogun, O. O. James, Y. K. Sanusi, and O. H. Olayinka, "Green synthesis and characterization of zinc oxide nanoparticles using bashful (Mimosa pudica), leaf extract: a precursor for organic electronics applications," *SN Appl Sci*, vol. 2, no. 3, p. 504, **2020.** https://doi.org/10.1007/s42452-020-2127-3

[92] W. Muhammad, N. Ullah, M. Haroon, and B. H. Abbasi, "Optical, morphological and biological analysis of zinc oxide nanoparticles (ZnO NPs) using *Papaver somniferum* L.," *RSC Adv*, Vol.**9**, No.**51**, pp.**29541–29548, 2019.** https://doi.org/10.1039/C9RA04424H

[93] H. Chandra, D. Patel, P. Kumari, J. S. Jangwan, and S. Yadav, "Phyto-mediated synthesis of zinc oxide nanoparticles of Berberis aristata: Characterization, antioxidant activity and antibacterial activity with special reference to urinary tract pathogens," *Materials Science and Engineering: C*, Vol.**102**, pp.**212–220, 2019.** https://doi.org/10.1016/j.msec.2019.04.035

