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Review On: Green Synthesis of Zinc Oxide Nanoparticles by Using Leaves and Its Applications.

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ABSTRACT: Nano chemistry, the branch of chemistry that deals with the design, synthesis, and application of materials at the nanoscale, has gained significant attention due to the unique physicochemical and biological properties exhibited by nanoparticles. Among various nanomaterials, zinc oxide nanoparticles (ZnO NPs) have attracted interest because of their multifunctional applications in the field of medicine, the environment, and industry. Green protocol of zinc oxide nanoparticles using extract of plant leaves is a sustainable and eco-friendly alternative to conventional methods. Phytochemicals in leaves act as natural reducing and stabilizing agents, enabling simple and cost-effective nanoparticle formation. This review focus on the biosynthesis of ZnO NPs using various leaves extracts and their versatile applications, including antibacterial, antifungal, antioxidant, anti-inflammatory and photocatalytic. These biosynthesised nanoparticles show promising biological and environmental applications, challenges remain in scaling up production, ensuring reproducibility, and evaluating long-term safety. This review reports that the specific applications and efficiency of the nanoparticles often depend on the particular phytochemical composition of the extract used, which influences the final size, shape, and stability of synthesised ZnO NPs. By consolidating current studies, this review highlights the potential of green-synthesised zinc oxide NPs and encourages future research toward practical applications.

KEYWORDS: Nanoparticles, Green Route, ZnO, etc.

I. INTRODUCTION

The current generation focuses on nanotechnology and nanoparticles, making it one of the most active areas in materials science research [1]. The widespread use of metallic nanoparticles is due to the numerous unique properties they possess [2,3]. The methodologies used for synthesizing nanoparticles are primarily categorized into three groups: physical methods, chemical methods, and green synthesis methods. A significant aspect of chemical synthesis techniques is their reliance on expensive and hazardous reagents, as well as energy-intensive processes, which contribute to their environmental deleterious effects. Furthermore, these methods often yield substantial byproducts, utilise concentrated reducing agents, and may involve elevated levels of radiation, alongside potential contamination from precursor materials. Such factors pose considerable environmental and biological risks, particularly when considered at a larger scale [4-7]. Interest in this field has decisively shifted toward "green chemistry" and the bioprocessing approach. Green Chemistry provides guiding principles for chemists aiming for more sustainable practices. Therefore, it has now opened up a new era of safe nanotechnology [8,9]. In this method, vegetables, leaves, and fruits are used to produce NPs, which are friendly, associated with a low cost, available on a large scale and are easy to get [10,11]. Phytochemicals already present in plant extracts, such as glycosides, flavonoids, polyphenols, terpenoids, alkaloids, amino acids, polysaccharides and enzymes, act as capping, stabilising, and reducing agents, simplifying the synthesis process and enhancing its safety, sustainability [12].

The extraction of leaves is used to produce zinc oxide nanoparticles through a sustainable and environmentally friendly process known as green synthesis has garnered considerable interest as a viable contender for various biomedical applications due to their favourable properties, including biocompatibility, low toxicity, and cost-effectiveness [13,14]. Nano-sized ZnO exhibits varying morphologies and shows robust biological properties, and has been used in several sectors for its antibacterial, anticancer, antioxidant, anti-inflammatory, and wound-healing properties. Additionally, it is important as a photocatalyst due to its utility in hydrogen generation, degradation of dye and pollution remediation [15,16]. Zno NPs are among the most commonly used metal oxide nanoparticles because of their distinctive chemical and optical properties can be easily modified as these depend on morphology and the band gap [17]. Considering all aspects, the objective of this review article is to explore the general green synthesis procedure for ZnO nanoparticles and their applications. This review comprises a compilation of recent advances with clear illustrations for a better understanding of the importance of zinc oxide NPs.

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II. RELATED WORK

General Synthesis of Zinc Oxide Nanoparticles by Using Leaves Extract:

The general procedure for synthesizing zinc oxide nanoparticles (ZnO NPs) using leaves extract involves a sequence of simple, low-cost, and environmentally benign steps. Fresh, disease-free leaves of the plant such as *Syzygium Cumini [19], Laurus nobilis [21]*, *Moringa oleifera [29], Aloe vera [32], etc,* are collected and washed thoroughly with distilled water to remove surface impurities and dust, followed by shade-drying. A measured amount of leaves is then cut into small pieces and boiled in distilled water to prepare the aqueous extract, which is subsequently filtered to obtain a clear phytochemical-rich solution. This extract is then added dropwise to a zinc precursor solution (such as zinc acetate, zinc nitrate [55]) under constant stirring. The bioactive compounds (phytochemicals) present in the extract act as natural reducing and stabilizing agents, facilitating the reduction of zinc ions and their conversion into zinc oxide nanoparticles.

The reaction mixture is typically maintained at a controlled temperature and pH to optimise nucleation and growth of nanoparticles. A visible colour change usually indicates nanoparticle formation. The resulting colloidal suspension is aged, centrifuged, and repeatedly washed with distilled water and ethanol to remove unbound phytochemicals and impurities. The purified pellet is dried in an oven and further calcined at appropriate temperatures (typically 300–500 °C) to obtain crystalline Zinc oxide nanoparticles. The synthesised zinc oxide nanoparticle from different leaves extract is characterised using techniques such as UV–Visible spectroscopy, FTIR, XRD, SEM and TEM, to confirm their optical, morphological and structural properties. This standardised green synthesis protocol highlights the simplicity and effectiveness of plant-mediated fabrication of zinc oxide nanoparticles, making it a valuable approach in sustainable nanotechnology. [18]

Summary of Leaves-Mediated Synthesis of Zinc Oxide Nanoparticles, Morphology and Application

Zinc oxide nanoparticles synthesised by using various leaves extracts have attracted considerable attention due to their significant photocatalytic and biomedical applications. The summarised Table 1 highlights these applications, and the effect of different leaves extracts on the morphology and properties of nanoparticles, along with consideration of future challenges and potential outcomes.

Table 1: Leaves-mediated synthesis of zinc oxide nanoparticles, morphology and application

Biological Source (leaves)	**Particle Size(nm)**	**Morphology /shape of Particles**	**Applications**	**References**
Syzygium cumini	10-12.55	Hexagonal, wurtzite	Photo-catalytic activity	[19]
Solanum nigrum	20-30	Hexagonal, wurtzite, quasi-spherical	Antibacterial activities	[20]
Laurus nobilis	47.27	hexagonal wurtzite,	Antibacterial activity, Anticancer activity	[21]
Ocimum Tenuiflorum	13.86	hexagonal, hexagonal shape	Industrial applications	[22]
Carica papaya	50	hexagonal wurtzite, spherical	Photocatalytic and photovoltaic	[23]
Acmella caulirhiza	97.05	Spherical	Antibacterial activity, Antioxidant activity, anti-inflammatory, and haemolytic treatments.	[18]
Quercus robur	20-60	hexagonal wurtzite	Antimicrobial agents, water purification, and environmental catalysis, Photocatalytic properties.	[24]
Secamone emetica	55.38	Hexagonal wurtzite, Spherical	Biological applications and photocatalytic activity	[25]
Passiflora foetida	50-90	Spherical shape	Anticancer, antioxidant, antibacterial	[26]
Citrus bergamia	35	Hexagonal	Photocatalysis	[27]
Merremia quinquefolia	43-70	Rod-like shapes	Antioxidant, anti-inflammatory, anticancer, antibacterial, biocompatible	[28]
Moringa oleifera	5.52 -41.59	Hexagonal, Spherical	Degradation of crystal violet dye	[29]

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Garcinia mangostana	14.21	Hexagonal wurtzite, Spherical	Antibacterial	[30]
Syzygium cumini	35	Hexagonal wurtzite	Anticancer, antimicrobial, antioxidant, and anti-corrosive	[31]
Aloe vera	25	Wurtzite, irregular shapes	Antimicrobial and Antioxidant	[32]
Cucumis maderaspatanus	15-25	Hexagonal wurtzite, spherical and flower shapes	Photocatalytic and antibacterial activity	[33]
Calendula officinali	28.23	Wurtzite hexagonal, spherical	Antioxidant and antibacterial activity	[34]
Pontederia crassipes	39	Hexagonal, wurtzite phase	Anti-breast cancer	[35]
Vitex negundo	19	Hexagonal wurtzite, spherical	Degradation of methylene blue	[36]
Hardwickia binata	25	Hexagonal quartzite phase, Spherical	Antioxidant, Anti-inflammatory, anti-cancer activity	[37]
Ephedra alata	25	Wurtzite, Spherical,	Photocatalytic activity, antibacterial activity, antioxidant, antibacterial	[38]
Ambrosia ambrosioides	32-37	Wurtzite-like, cluster-shaped	Photocatalytic Degradation	[39]
Salvia coccinea	5	spherical structure, rod-like shape	Antimicrobial, antioxidant and anticancer activity.	[40]
Calotropis gigantea	48-51	Hexagonal wurtzite, grain boundaries	Optoelectronics, antibacterial properties.	[41]
Epipremnum aureum	19.31	Hexagonal crystalline	Photocatalytic degradation of Congo red	[42]

Challenges:

- Producing a large amount with consistent quality remains difficult due to variation in extract composition, longer reaction times, and lower control over synthesis kinetics.
- Challenges remain in achieving precise control of optical, antimicrobial, catalytic or electronic properties.[43]

Future outlook:

Future research will focus on optimising their potency while minimising cytotoxicity to healthy cells. Also, NPs exhibit strong photocatalytic activity, enabling them to degrade pollutants and organic dyes under light exposure.

III. CONCLUSION

This literature review confirms that plant-mediated synthesis enables precise control over the size, shape, and morphology of ZnO nanoparticles, with phytochemicals playing a key role in their reduction, stabilisation, and enhanced biological performance. Green-synthesised zinc oxide NPs consistently show strong anticancer, antioxidant, antibacterial, and anti-inflammatory activities due to the natural capping agents present in leaf extracts. ZnO NPs produced from *Salvia coccinea, Merremia quinquefolia* leaves extract demonstrate stable and high bioactivity, attributed to phenolic and alkaloid compounds. Additionally, plants such as *Syzygium cumini, Citrus bergamia, Moringa oleifera, Vitex negundo, Epipremnum aureum , and Ambrosia ambrosioides* yield ZnO NPs with notable photocatalytic activity. Collectively, these findings highlight the significant potential of plant-derived phytochemicals in engineering multifunctional ZnO nanoparticles for biomedical and environmental applications.

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