Green Synthesis of ZnO Nanoparticles

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MASTER OF SCIENCE

IN

CHEMISTRY

SUBMITTED BY

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CANDIDATE'S DECLARATION

I, Chetna Kumari (2K23/MSCCHE/84) and Ranjit (2K23/MSCCHE/34) students of M.Sc. (Chemistry) hereby declare that the project Dissertation titled " **Green Synthesis of ZnO Nanoparticles** " which is submitted by us to the Department of Applied Chemistry. Delhi Technological University, Delhi, in the partial fulfillment of the requirement for the award of the degree of Master of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship or other similar title or recognition.

Place: Delhi

Date: 20 June 2025

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CERTIFICATE

I/We hereby certify that the Project Dissertation titled " Green Synthesis of ZnO Nanoparticles " which is submitted by Chetna Kumari (2K23/MSCCHE/84) and Ranjit (2K23/MSCCHE/34). Department of Applied Chemistry, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the Master of Science, is a record of the project work carried out by the student under my supervision. To the best of my/our knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere**.**

Place: Delhi

Date: 20th June 2025

PROF. ANIL KUMAR	**PROF. ROLI PURWAR**
(HEAD OF DEPARTMENT)	**(SUPERVISOR)**

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ABSTRACT

The extensive applicability and diverse characteristics of metallic oxide nanomaterials in the fields of sustainable remediation, biology, and electronics render them a promising material. Among the various metal oxides, zinc oxide (ZnO) nanoparticles are particularly noteworthy due to their high exciton binding energy (60 meV) and wide band gap (3.37 eV). Techniques such as metallurgical processes, sol-gel methods, mechanochemical approaches, and laser ablation have all been employed to synthesize ZnO nanoparticles. In comparison to more traditional techniques, green synthesis is considered more stable, less hazardous, and more cost-effective. Any part of the plant—including the stem, leaves, flowers, fruit, and roots—may be utilized as the phytochemical concentrate, which functions as a capping and reducing agent during the synthesis process. In addition to aqueous plant extract, a precursor such as zinc acetate dihydrate, zinc sulfate, or zinc nitrate is incorporated during the synthesis. Among the various reducing and capping agents found in the plant extract are phenolic acids, flavonoids, alkaloids, terpenoids, proteins, polysaccharides, saponins, and tannins. Furthermore, fungi, bacteria, algae, and plant extracts may all be employed in green synthesis. This study thoroughly examines the different plant extracts utilized in the production of ZnO nanoparticles. Additionally, this publication delivers an outline of current advancements in the synthesis of zinc oxide nanoparticles using fungi, bacteria, and algae.

Keywords: - ZnO nanoparticles, Green synthesis, Plant extract, Fungi, Bacteria, Algae

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1. INTRODUCTION AND OBJECTIVES OF WORK

1.1. Background of Study

The subject of material science has made substantial use of nanotechnology in recent decades. The first effort at this concept was made by American physicist Richard Feynman in his 1959 lecture [1]. Nanotechnology focuses on the fabrication of matter at the nanometre scale level, generally in the range of 1-100 nanometres (nm), including metal nanowires [3], carbon nanotubes [2], and nanoparticles with unique mechanical and electrical properties. Nanoparticles are very interesting due to their minute size and extensive surface area-to-volume ratio [4], which gives them enhanced attributes than their bulk state, including antibacterial, magnetic, optical capabilities, catalytic, and electrical [5].

1.2. Zinc Oxide Nanoparticles

Zinc oxide (ZnO) and Titanium (IV) dioxide (TiO2) are examples of metal oxide nanoparticles that were broadly analyzed by several researchers owing to their high potential under challenging processing circumstances [6]. The metallic oxide nanomaterial, like zinc oxide nanoparticles (ZnO NPs), possesses a density of 5.606 g cm-1, is insoluble in water, and has a refractive index of 2.0041. They are also nontoxic. It also has a high boiling 1975°C and a melting temperature of 2360°C. The hexagonal-wurtzite atomic arrangement of ZnO is demonstrated in Figure 1, where atomic oxygen (white orbs) is tetrahedrally coupled to zinc atoms (black orbs).

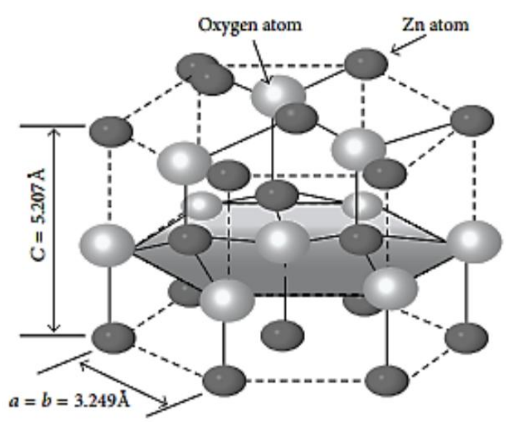

Figure 1. Hexagonal-Wurtzite structure of Zinc Oxide

The most alluring aspect of employing ZnO NPs is their wide range of applications, some of which are observed in Figure 2.

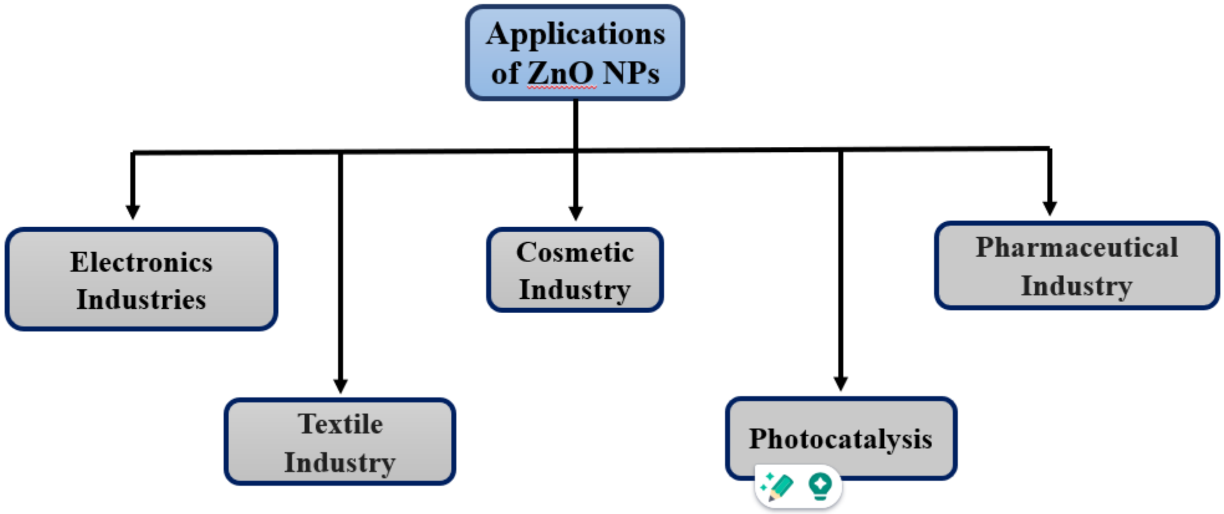

Figure 2. Application of Zinc Oxide Nanoparticles

ZnO NPs are semiconductor materials with a large excitation binding energy of 60 MeV and a broad band gap energy of 3.37 eV [7]. ZnO NPs are another potent photocatalyst that can be used to degrade organic dyes because of their semiconductor characteristics, which are similar to those of TiO2 NPs, a well-known system that has a 3.2 eV band gap energy [8].

1.2.1. Synthesis Methods of Zinc Oxide Nanoparticles

Researchers have described a variety of synthetic approaches for creating the nanoparticles represented in Figure 3.

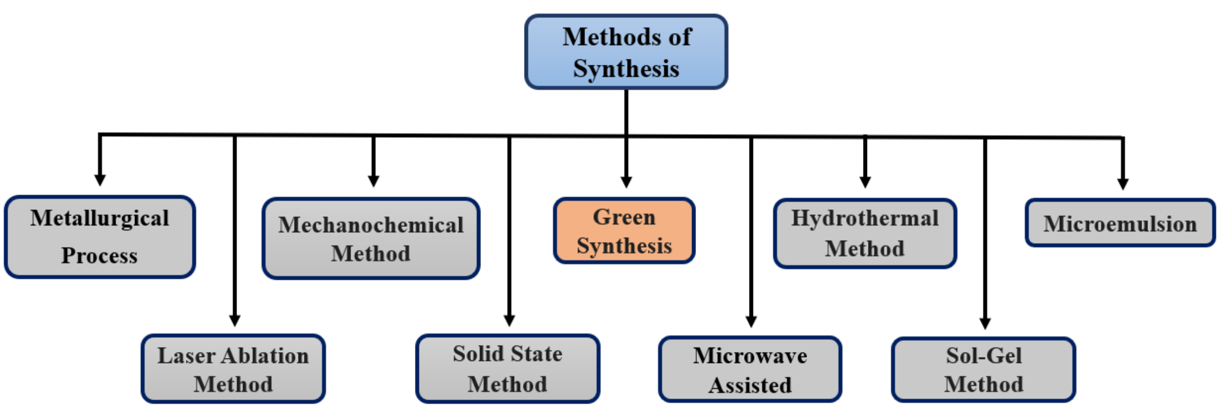

Figure 3. Methods of fabrication

Controlled synthesis of nanoparticles with targeted properties like shape, size, and physicochemical characteristics relies on optimized reaction parameters, particularly pressure and temperature during the reaction, along with the careful selection of a stabilizing agent to prevent agglomeration and a reducing agent to convert the metal ion precursor [9]. Classical synthesis techniques commonly involve non-eco-friendly chemical and physical agents for reduction and stabilization that are detrimental to the ecosystem. Moreover, these approaches are generally expensive, utilize a significant amount of energy, and produce toxic by-products. [10].

However, a more environmentally friendly method of production using the biological method can effectively reduce these issues. This technique uses plant extract or microorganisms like fungi and bacteria. According to reports, plant extract is more advantageous than microbes because it doesn't require expensive isolation, cultivation, or maintenance, and it can produce a high yield quickly enough for industrial scale consideration [11]. Due to the diversity of bioactive components, including alkaloids, terpenoids, tannins, phenolics, amino acids, proteins, enzymes, polysaccharides, saponins, and vitamins, plant extracts serve as effective alternatives to traditional stabilizing and reducing agents [12]. Furthermore, because some fruit peels are readily available and also rich in these bio-components, different fruit peel extracts are of significant interest because they share some characteristics with the plant extract. It is a very good practice in the interim since it reduces the environmental impact of the waste produced and makes full use of it, which strongly satisfies the green chemistry criteria. Research shows that banana peel extract is a valuable resource for nanoparticle synthesis due to its rich composition of dopamine, L-DOPA, and a mix of reducing agents and stabilizing macromolecules such as lignin, pectin, and hemicellulose [13]. Dopamine and L-DOPA are catecholamines with potent antioxidant action because they have a catechol functional group [14,15].

Objectives of work

- A study reviewing the use of plant extracts, fungi, bacteria, and algae for the synthesis of Zinc Oxide nanoparticles, focusing on the mechanism of synthesis, particle size, precursor used, and specific characteristics such as shape and calcination temperature.
- To fabricate Zinc Oxide nanoparticles via plant-based synthesis by utilizing leaf extracts of different plants such as *Citrus limon* (lemon), *Azadirachta indica* (neem), *Syzygium cumin* (jamun), *Punica granatum* (pomegranate), *Parthenium hysterophorus* (congress grass), and to analyze of synthesized nanoparticles using analytical techniques like UV-Vis spectroscopy, zeta potential, and particle size analysis.

2. LITERATURE REVIEW

We will likely be surrounded by nanotechnology in the near future, as it could be the next big thing in science. From its inception as a potent tool for basic and applied science, it has garnered significant interest within the scientific community. While biology offers nanotechnology inspiration models and bio-assembled components, nanotechnology itself provides the tools and technological platform for studying and transforming biological systems. Nanobiotechnology is the application of nanoscale ideas and techniques to understand and modify bio systems (both living and non-living) through the development of novel devices and systems integrated from the nanoscale using biological principles and materials [16]. Measurements at the subcellular level and our understanding of the cell as a highly ordered, self-repairing, self-replicating, information-rich molecular machine have both advanced significantly [17] and [18]. Smalley divided nanotechnologies into two categories: wet and dry. The former was used to describe living biosystems, while the latter was used to study man-made objects at the nanoscale [19]. It is increasingly common for commercially available products to contain nanoparticles.

Figure 4 highlights several biobased materials that offer a sustainable approach for the fabrication of zinc oxide nanoparticles. The image shows two main biobased sources for the synthesis process: microbes and plants. ZnO nanoparticles can be formed from several plant materials, such as leaves like those of *Azadirachta indica* (neem) and *Berberis aristata* (Indian barberry); fruits like those of *Myristica fragans* (nutmeg) and *Alianthus altissima* (tree of heaven); flowers like those of *Hyssopus officinalis* (Jufa) and *Vinca rosea* (Madagascar periwinkle); stems like those of *Amygdalus scoparia* (wild almond) and *Jatropha* (nettle spurge); seeds like those of *Mangifera indica* (mango) and Grapes; roots (like those of *Beta vulgaris* (beetroot); and fruit peel, such as the *Punica granatum* (pomegranate). ZnO nanoparticles can also be synthesized using microorganisms such as bacteria (like *Pseudomonas aeruginosa* and *Lactobacillus sporogens*), fungi (like *Aspergillus fumigatus* and *Cordyceps militaris*), and algae (like *Sargassum muticum* and *Spirogyra hyaline*).

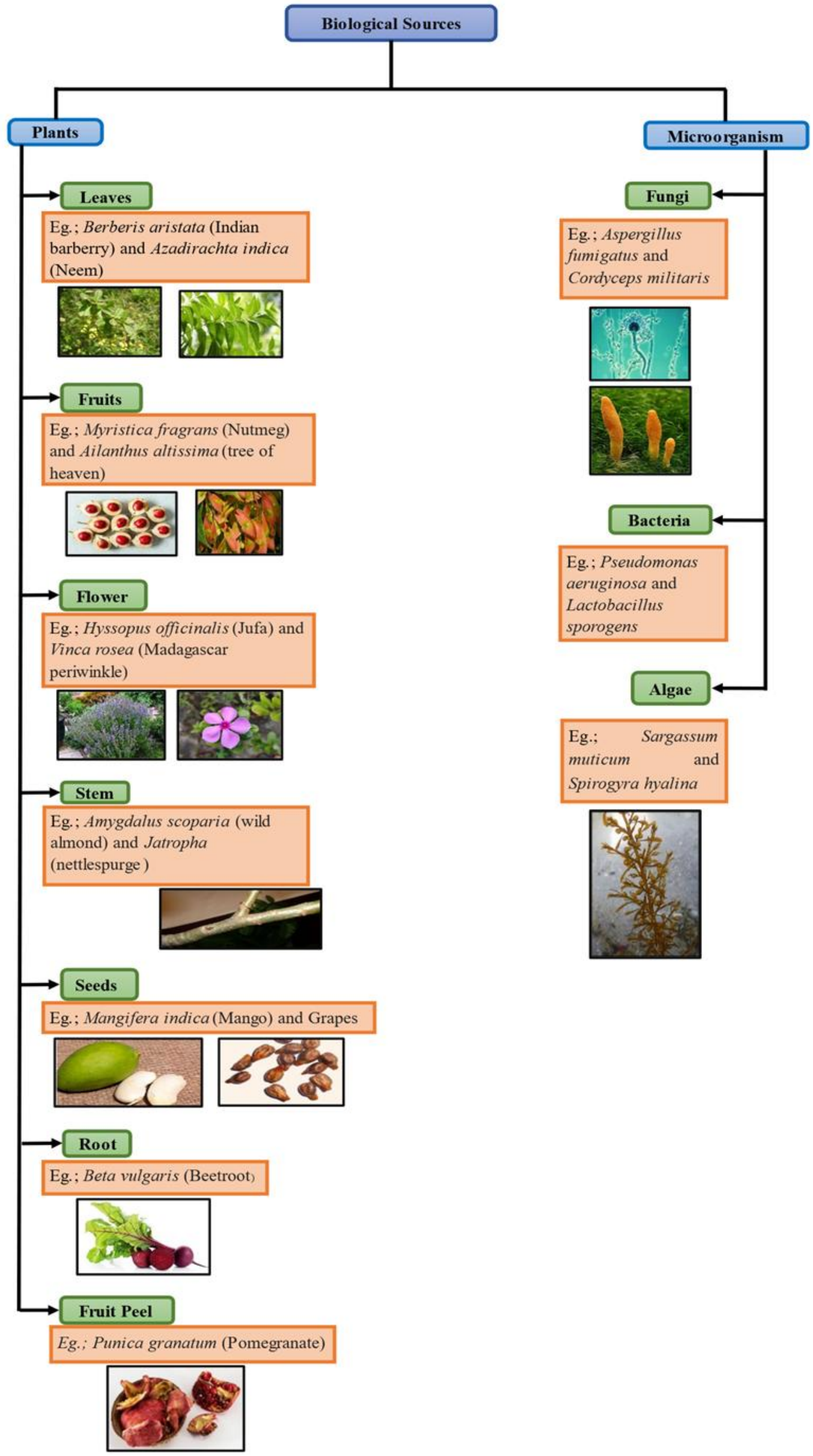

Figure 4. Biobased compounds employed to generate ZnO nanoparticles via green synthesis

2.1. Plant leaves used for the synthesis of ZnO nanoparticles

Plant leaves from several classes of species are used to synthesize ZnO nanoparticles; some of these are included in Table 1, like *Aloe barbadensis, Azadirachta indica, Berberis aristata, Calliandra haematocephala, Calotropis gigantea, Camellia sinensis, Cassia fistula, Corymbia citriodora, Dlichos lablab* L., *Eucalyptus globules, Justicia wynaadensis, Laurus nobilis, Leea asiatica*, *Melia azedarach, Origanum majorana, Pelargonium zonale, Pisonia alba, Prosopis farcta*, *Raphanus sativus var. Longipinnatus, Solanum nigrum,* and *Vinca rosea* which consist of reducing agents like polyphenols (aloin), Terpenoids (Nimbin, Azadirachtin), Alkaloids (Bis isoquinoline), Flavonoids (Myricitrin, Quercitrin), Flavonoids (Kaempferol, Varinging), Polyphenols (Catechins), Flavonoids (Porocyanidin, Biflavonoids), Terpenoids (Cintronellal and Linalool), Flavonoids (Kievitone), Aldehyde (Citronellal), Phenyloxazole, Aporphinic alkaloids (Cryptodorin and Actinodaphnin), Sorbitol, Limonoids (Azadirachtin, Nimbin, Melianoninol), Hydroquinone, Alkaloid (Quinine), Stigmasterol, Alkaloid (5-hydroxytryptamine, Tryptamine), Tannins, Flavonoids (Naringenin, Rutin), and Alkaloids (Vinblastine, Vincristine, Vindollidine, Vindoline, Vindolicine) respectively, showing different morphologies like spherical shaped, hexagonal disk-shaped, needle-like shape, flower-like shape, irregular shaped, polyhedron shaped, triangular shaped, rod-like shape and quasi-spherical shape, and have the particle size distributed from 2 nm - 728 nm [20-40].

Table 1. Plant leaves used for the synthesis of ZnO nanoparticles

Sr. No.	**Plant Name**	**Reducing Agents**	**Size (nm)**	**Precursor used**	**Precursor Concentration**	**Specifications**	**Reference**
1.	*Aloe barbadensis* (Aloe vera)	Polyphenols (aloin)	20-40	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Spherical in shape Calcination: Temp.: 500 °C Time: 1 hour	[20]
2.	*Azadirachta indica* (Neem)	Terpenoids (Nimbin, Azadirachtin), Flavonoids (quercetin)	11-40	$[Zn(CH_3COO)_2.2H_2O]$	2 M	Hexagonal disk-shaped	[21]
3.	*Berberis aristata* (Indian barberry)	Alkaloids (Bis isoquinoline, protoberberine)	5-25	$[Zn(CH_3COO)_2.2H_2O]$	0.1 M	Needle-like shape	[22]

4.	*Calliandra haematocephala* (Red powder puff)	Phenolic acids (Gallic acid, Caffeic acid), Flavonoids (Myricitrin, Quercitrin, Isoquercitrin)	6-30	$[Zn(CH_3COO)_2.2H_2O]$	0.05 M	Flower-like nanostructures	[23]
5.	*Calotropis gigantea* (giant milkweed)	Flavonoids (Kaempferol, Varinging, Quercitrin, Hespritin) Phytol, Tannins, Sitosterol, Glucoside, Sigmasterol, Quinine, ellagic acid, Acalyphamide, 2-Methylanthraquinone, Resins, Tri-O-Methyl	8-12	$[Zn(CH_3COO)_2.2H_2O]$	200 mM	Spherical shaped	[24]
6.	*Camellia sinensis* (Tea Plant)	Polyphenols (Catechins), Flavonoids (Quercetin), Phenolic acids (Gallic acid, Caffeic acid),	6–112	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Spherical in shape	[25]

		Alkaloids (Caffeine)					
7.	*Cassia fistula* (golden shower)	Flavonoids ((-)-Epiafzelechin, (-)-Epiafzelechin-3-O-glucoside, (-)-Epicatechin, Porocyanidin, Biflavonoids, Triflavonoids)	5-15	$[Zn(NO_3)_2.6H_2O]$	2 M	Sponge-like irregular shaped Calcination Temp.: 400 ± 10 °C	[26]
8.	*Corymbia citriodora* (Lemon scented gum)	Terpenoids (Cintronellal and Linalool), Flavonoids (Catechin), Phenolic acid (Gallic acid, Protocatechuic acid, p-Coumaric acid)	20-120	$[Zn(NO_3)_2.6H_2O]$	0.5 M	Polyhedron shaped	[27]
9.	*Dolichos lablab* L. (Hyacinth bean)	Oxalate, Saponin, Alkaloids, Polyphenols, Flavonoids (k Kievitone).	36	$[Zn(CH_3COO)_2.2H_2O]$	2.73 mmol	Hexagonal and triangular-shaped	[28]

10.	*Eucalyptus globules* (blue gum)	Carvacrol (Phenolic compound), Citronellal (Aldehyde), Myrtenal, and Borneol (Monoterpenoids)	52-70	$[Zn(NO_3)_2.6H_2O]$	1 mM	Spherical shaped	[29]
11.	*Justicia wynaadensis* (Nees)	1,3,5-Trioxane, Coumarin (2H-1-Benzopyran-2-One), 2-D(1)-4-Phenyloxazole, 1,3,4,5-Terta-O-Acetyl,2,6,7-Tri-O-Methyl-D(1)-Heptitol	39	$[Zn(NO_3)_2.6H_2O]$	0.33 M	Hexagonal shaped Calcination Temp: 350 °C Time: 3 hours	[30]
12.	*Laurus nobilis* (Bay laurel)	Aporphinic alkaloids (Cryptodorin and Actinodaphnine), Flavonoids (Kaempferol), Phenylpropanoids (Eugenol, Methyl	20-30	$[Zn(NO_3)_2.6H_2O]$	0.84 M	Spherical shaped Calcination Temp: 400 °C Time: 3 hours	[31]

		eugenol), Sesquiterpenes (Dehydrocostus lactone, Santamarine), Monoterpenes (Limonene, Eucalyptol), α-Tocopherol (vitamin E), and β-Sitosterol					
13.	*Leea asiatica* (Asian leea)	Diethyl mercaptal (diethyl sulfide), Sorbitol, Butanediol, Sulfide.	27-728	$[Zn(CH_3COO)_2.2H_2O]$	1 M	Rod-like shape Calcination Temp: 500 °C Time: 2 hours	[32]
14.	*Melia azedarach* (Cape lilac)	Flavonoids (quercetin, Rutin), Limonoids (Azadirachtin, Nimbin, Melianoninol), Phenolic compounds (Tannins).	2.72	$[Zn(CH_3COO)_2.2H_2O]$	0.01 M	Spherical shape	[33]
15.	*Origanum majorana*	Hydroquinone, Phenolic terpenoids,	19	$[Zn(NO_3)_2.6H_2O]$	1.82 M	Hexagonal shaped	[34]

	(Marjoram)	Triacontane, Phenolic glycosides, Sitosterol, Flavonoids, Tannins					
16.	*Pelargonium zonale* (Geranium)	Glucuronic acid, Flavonoids, Tannins, Phenolic compounds, Amide I group, Alkaloid (Quinine)	61	[$Zn(NO_3)_2.6H_2O$]	0.33 M	Spherical shaped Calcination Temp: 400 °C Time: 2 hours	[35]
17.	*Pisonia alba* (Birdlime tree)	D-Pinitol, Phytol, Stigmasterol, Phenolic compounds, Flavonoids	14.0-14.17	[$Zn(CH_3COO)_2.2H_2O$]	0.1 M	Hexagonal Calcination Temp: 500 °C Time: 2 hours	[36]
18.	*Prosopis farcta* (Syrian mesquite)	Phenolic compounds, L-arabinose, Lectins, Alkaloid (5-hydroxytryptamine, Tryptamine), Flavonoids (Apigenin,	40–80	[$ZnSO_4$]	3 mM	Hexagonal Calcination Temp: 600 °C Time: 2 hours	[37]

		Quercetin), Tannins					
19.	*Raphanus sativus var. Longipinnatus* (winter radish)	Flavonoids, Tannins, Phenolic compounds, Alkaloids.	66.43	$[Zn(CH_3COO)_2.2H_2O]$	0.1 M	Hexagonal and spherical in shape	[38]
20.	*Solanum nigrum* (Black nightshade)	Glycoproteins, Glycoalkaloids, Phenolic compounds (Gallic acid, Protocatechuic acid (PCA), Caffeic acid), Flavonoids (Epicatechin, Catechin, Naringenin, Rutin)	20-30	$[Zn(NO_3)_2.6H_2O]$	0.33 M	Quasi-spherical shaped Calcination Temp: 400 °C Time: 2 hours	[39]
21.	*Vinca rosea* (Pink Periwinkle)	Alkaloids (Vinblastine, Vincristine, Vindollidine, Vindoline, Vindolicine)	16–41	$[Zn(NO_3)_2.6H_2O]$	0.3 M	Hexagonal Calcination Temp: 550 °C Time: 2 hours	[40]

2.2. Plant stem used for the synthesis of ZnO nanoparticles

The stem of several plant species have served as precursors for the fabrication of ZnO nanopartilces, some of which are listed in Table 2 like *Cissus quadrangularis* L., *Gliricidia sepium*, *Mussaenda frondosa* L., *Nepeta nepetella,* and

Nicotiana tabacum which consist of reducing agents like nitroso and butanoic acid, p-coumaric acid and caffeic acid, tannins, iridoid triterpenes and monoterpenes, and lupeol, oleanolic acid, anthocyanins, and ursolic acid respectively, showing different morphologies like spherical shaped, hexagonal shaped and rod-like shape, and have the particle size distributed from 8 nm - 182 nm [41-45].

Table 2. Plant stem used for the synthesis of ZnO nanoparticles

Sr. No.	Plant Name	Reducing Agents	Size (nm)	Precursor used	Precursor Concentration	Specifications	Reference
1.	*Cissus quadrangularis* L. (Veldt grape)	DL-Methyltartronic acid, 2-hydroxy-2-methyl, Nitroso, Butanoic acid, Tri fluoroacetoxy pentadecane, methyl ester	88-182	$[Zn(CH_3COO)_2.2H_2O]$	1 mM	Spherical shaped	[41]
2.	*Gliricidia sepium* (Mexican lilac)	Apegnin-7-O-glucoside, p-coumaric acid, caffeic acid, p-hydroxybenzoic acid, cinnamic acid, Syringic acid, quercetin, protocatechuic acid and	8.45	$[Zn(CH_3COO)_2.2H_2O]$	0.02 M	Hexagonal shaped	[42]

		Ferulic acid, Vanillic acid					
3.	*Mussaenda frondosa* L. (Dhobi tree)	Amides present in proteins (aliphatic and aromatic), carboxylic acids, Phenolic compounds, Flavonoids, Tannins	9-12	[$Zn(NO_3)_2.6H_2O$]	0.33 M	Spherical shaped Calcination Temp: 400℃ Time: 10-15 minutes	[43]
4.	*Nepeta nepetella* (Lesser Cat-mint)	Coniferin, p-coumaric acid, 4-hydroxybenzoic acid, ferulic acid, vanillic acid, nepetoidin B, rosmarinic acid, Caffeic acid, iridoid triterpenes, and monoterpenes	18.1 ± 1.3	[$ZnSO_4$]	0.5 M	Spherical shape Calcination Temp: 500 ℃ Time: 2 hours	[44]
5.	*Nicotiana tabacum* (Tobacco)	Lupeol, oleanolic acid, anthocyanins,	15	[$Zn(CH_3COO)_2.2H_2O$]	0.16 M	Rod-like shape Calcination Temp: 400 ℃	[45]

		ursolic acid, quercetin, proanthocyanidins, kaempferol, sitosterol				Time: 3 hours	

2.3. Plant roots used for the synthesis of ZnO nanoparticles

The roots of several plant species have been employed to fabricate ZnO nanoparticles; some of these are included in Table 3 like *Phoenix dactylifera, Polygala tenuifolia, Rubus fairholmainus, Rumex abyssinicus Jacq., Scutellaria baicalensis,* and *Zingiber officinale* which consist of reducing agents like Phenolic compounds (Gallic acid, Caffeic acid), saponins (3,4,5-tri-methoxy-cinnamic acid, onjisaponins A, B, C, D, E, F and G), benzoic acid and benzoate, anthraquinones and phlobataine, flavonoids (Baicalin, Wogonoside), and Terpenes (Borneol, Geraniol, Limonene, Linalool, α-Zingiberene) respectively, showing different morphologies like spherical shaped and irregular-spherical shape, and size of particles distributed from 11 nm - 74 nm [46-51].

Table 3. Plant roots used for the synthesis of ZnO nanoparticles

Sr. No.	**Plant Name**	**Reducing Agents**	**Size (nm)**	**Precursor used**	**Precursor Concentration**	**Specifications**	**Reference**
1.	*Phoenix dactylifera* (Date palm)	Phenolic compounds (Gallic acid, Caffeic acid, Flavonoids (Kaempferol, Quercetin, Saponins), Tannins	30.87-47.89	$[Zn(CH_3COO)_2.2H_2O]$	0.6 M	Spherical shape Calcination Temp: 450 °C Time: 3 hours	[46]
2.	*Polygala tenuifolia* (Chinese senega root)	Xanthone derivatives, Triterpenes, saponins (3,4,5-	33.03-73.48	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Spherical shape	[47]

		trimethoxy-cinnamic acid, onjisaponins A, B, C, D, E, F, and G, 1,2,3,6,7-penta-methoxyxanthone, 6-hydroxy-1,2,3,7-tetramethoxy xanthone), Flavonoids (Linarin, Isorhamnetin, Kaempferol, Quercetin)					
3.	*Rubus fairholmainus* (Vettilamullu)	Isopentyl benzoate, Cis-2-(isopentyloxycarbonyl) benzoic acid, 4-methylpentyl, 2-(5-methylhexyl) benzoic acid, benzoate, 3-	11.34	$[Zn(NO_3)_2.6H_2O]$	0.5 M	Spherical shape	[48]

		(iminomethyl)-2,4-dimethylphenol,					
4.	*Rumex abyssinicus Jacq.* (Spinach rhubarb)	Anthraquinones, Phlobataine, Polyphenols, Tannins, Flavonoids, Alkaloids	15	[$Zn(CH_3COO)_2.2H_2O$]	0.05 M	Spherical and irregular in shape Calcination Temp: 500 °C	[49]
5.	*Scutellaria baicalensis* (Chinese skullcap)	Flavonoids (Baicalin and its aglycone Bacialein, and Wogonoside and its aglycone Wognin)	50	[$Zn(NO_3)_2.6H_2O$]	1 mM	Spherical shape	[50]
6.	*Zingiber officinale* (Ginger)	Flavonoids, Phenolic compounds (gingerols, shagols, zingerone), Paradol, Terphineol, Terpenes (Geraniol, Linalool, Limonene,	30-50	[$Zn(CH_3COO)_2.2H_2O$]	0.01 M	Spherical shape	[51]

		α-Zingiberene, Borneol)					

2.4. Plant flowers used for the synthesis of ZnO nanoparticles

Zinc Oxide nanoparticles can be fabricated from a variety of floral species, some of which are given in Table 4 like *Anchusa azurea,* Bougainvillea, *Calendula officinalis, Canna indica* L., *Hylotelephium telephium, Jacaranda mimosifolia, Peltophorum pterocarpum, Senna auriculata, and Trifolium pratense* which consist of reducing agents like terpenoids (Germacrene D, γ-eudesmol, δ-cadinene), phytol and linalool, carotenoids, phytochemicals (Anthocyanins, Anthocyanidin Glycosides), tetradecanoic acid and pentadecanoic acid, oleic acid, coumarins, Phenolic acids (Chlorogenic acid, Caffeic acid, Gallic acid), and Isoflavones (Genistein, Daidzein, Biochanin A and Formononetin) respectively, showing different morphologies like hexagonal shape, spherical shape and irregular spherical shape and the size of particles ranges from 2 nm - 84 nm [52-60].

Table 4. Plant flowers used for the synthesis of ZnO nanoparticles

Sr. No.	**Plant Name**	**Reducing Agents**	**Size (nm)**	**Precursor used**	**Precursor Concentration**	**Specifications**	**Reference**
1.	*Anchusa azurea* (Garden anchusa)	Terpenoids (Germacrene D, γ-eudesmol, δ-cadinene), Tannins, Saponins, Flavonoids (Kaempferol, Isorhamnetin, Quercetin), Phenolic acids (Rosmarinic acid, Caffeic acid, Chlorogenic acid),	8-14	$[Zn(CH_3COO)_2.2H_2O]$	0.02 M	Hexagonal shape Calcination Temp: 100-200 °C Time: 2 hours	[52]

		Pigments (Lycopene, Anthocyanins)					
2.	Bougainvillea (Paper flower)	Terpenes, Phytol, linalool, methyl-2-hydroxybenzoate, α-ionone, pinitol	10-50	$[Zn(CH_3COO)_2.2H_2O]$	0.01 M	Spherical shape	[53]
3.	*Calendula officinalis* (Pot marigold)	Saponins, triterpenes, alcohol triterpenes, carotenoids, flavonoids, coumarins	17.66	$[Zn(NO_3)_2.6H_2O]$	0.33 M	Spherical shape	[54]
4.	*Canna indica* L. (Indian shot)	Phytochemicals (Anthocyanins, Anthocyanidin Glycosides, Polyphenols), Pigments (Lycopene), Flavonoids (Rutin, Kaempferol), Terpenoids (γ-eudesmol, δ-	25-40	$[Zn(NO_3)_2.6H_2O]$	0.13 M	Spherical shape Calcination Temp: 600 °C Time: 1 hour	[55]

		cadinol, γ-selinene)					
5.	*Hylotelephium telephium* (Orpine)	2'-Methylsulfinyl ethyl phenylglyoxylate, Tetradecanoic acid, Pentadecanoic acid, Terpenoids ((2E,6S)-6,7-Isopropylidene dioxy-2-hepten-1-ol)	36	$[Zn(NO_3)_2.6H_2O]$	1 mM	Irregular Spherical shape	[56]
6.	*Jacaranda mimosifolia* (Jacaranda)	Oleic acid (majorly), 1,6-dimethyldecahydronapthalene, Citronellyl propionate	2-4	$[C_{12}H_{26}O_{15}Zn]$ (Zinc gluconate hydrate)	0.1 M	Spherical shape	[57]
7.	*Peltophorum pterocarpum* (Yellow flamboyant)	Xanthoproteins, Coumarins, Saponins, Flavonoids, Phenolic compounds, Tannins, Carboxylic acids	69.45	$[Zn(NO_3)_2.6H_2O]$	0.33 M	Irregular spherical shape Calcination Temp: 400 °C Time: 2 hours	[58]

8.	*Senna auriculata* (Tanner's Cassia)	Tannins, Saponins, Glycosides (Sennosides A and B), Flavonoids (Kaempferol, Isorhamnetin, Quercetin), Phenolic acids (Gallic acid, Caffeic acid, Chlorogenic acid)	12	$[Zn(CH_3COO)_2.2H_2O]$	0.33 M	Irregular spherical shape Calcination Temp: 500 °C Time: 2 hours	[59]
9.	*Trifolium pratense* (Red clover)	Phenolic compounds, Tannins, Isoflavones (Genistein, Daidzein, Biochanin A, and Formononetin)	70-84	$[Zn(CH_3COO)_2.2H_2O]$	0.46 M	Spherical shape	[60]

2.5. Plant seeds used for the synthesis of ZnO nanoparticles

A variety of seeds from several plant species from which ZnO nanoparticles can be synthesized are listed in Table 5 like *Avena sativa, Caesalpinia crista, Citrullus colocynthis (L.), Cydonia oblonga, Eriobotrya japonica, Mangifera indica, Nigella sativa* L.*, Silybum marianum,* and *Syzygium cumini* which consist of reducing agents like phenolic acids (Hydroxybenzoic acid, p-Coumaric), coumarins, flavonoids (Isosaponarin, Isovitexin, Isoorientin), galacturonic acid, methylated and nonmethylated aldobionic acids, proteins, lipids and amygdalin, ascorbic acid, phenolic compounds (Thymoquinone, Thymol, Carvacrol), Isosilybin A and B, and Ellagic acid respectively, showing different morphologies like hexagonal shape, irregular spherical shape, block-like shape and cylindrical shape and have a particle size ranging from 17 nm - 80 nm [61-69].

Table 5. Plant seeds used for the synthesis of ZnO nanoparticles

Sr. No	Plant Name	Reducing Agents	Size (nm)	Precursor used	Precursor Concentration	Specifications	Reference
1.	*Avena sativa* (Oat)	Phenolic acids (Hydroxybenzoic acid, p-Coumaric acid, Vanillic acid, Ferulic acid, amino acids Caffeic acid), Carotenoids, Proteins, Starch, α-Tocopherols and α-Tocotrienols (Vitamin E), Phenolic alkaloids (Avenanthramides, β-glucan)	17.52	$[Zn(NO_3)_2.6H_2O]$	0.33 M	Hexagonal shape Calcination Temp: 400 °C Time: 2 hours	[61]
2.	*Caesalpinia crista* (Fever nut)	Alkaloids, Flavonoids, Tannins, Triterpenes, Coumarins	34.67	$[Zn(NO_3)_2.6H_2O]$	0.8 mM	Irregular shape	[62]
3.	*Citrullus colocynthis (L.)*	Cucurbitacins, Glycosides, Flavonoids (Isosaponarin,	20-35nm	$[Zn(NO_3)_2.6H_2O]$	10 M	Block-like shape	[63}

	(Bitter apple)	Isovitexin, Isoorientin), 3-O-methyl ether, Polyphenolic compounds					
4.	*Cydonia oblonga* (Quince)	Galacturonic acid, Methylated and Nonmethylated Aldobionic acids, Arabinose, Xylose	25	[$Zn(NO_3)_2.6H_2O$]	0.84 M	Spherical shape Calcination Temp: 400 °C, 500 °C and 600 °C Time: 2 hours each	[64]
5.	*Eriobotrya japonica* (Loquat)	Proteins, Lipids, Amygdalin, Phenolic acids (Caffeic acid, Hydroxycinnamic acid, Hydroxybenzoic acid, Chlorogenic acid), Flavonoids (naringenin, Kaempferol)	18-27	[$Zn(CH_3COO)_2.2H_2O$]	0.1-0.2 M	Spherical shape	[65]
6.	*Mangifera indica* (Mango)	Polyphenols, Tannins, Flavonoids,	40-70	[$Zn(NO_3)_2.6H_2O$]	10 mM	Spherical and cylindrical shapes	[66]

		Ascorbic acid (Vitamin C), and Terpenoids					
7.	*Nigella sativa* L. (Black cumin)	Alkaloids (Isoquinoline, Nigellicimine, Nigellicimine-N-oxide, Nigellidine, Nigellicine, Pyrazole), Terpenoids (p-Cymene, 4-Terpineol, Alpha-Hederin and Sesquiterpene Longifolene, t-Anethol, α-Pinene, Thymohydroquinone, Dithymoquinone), Phenolic compounds (Thymoquinone, Thymol, Carvacrol)	20	$[Zn(NO_3)_2.4H_2O]$	0.63 M	Spherical shape	[67]
8.	*Silybum marianum*	Isosilybin A and B, Silychristin, Silydianin,	18 ± 1	$[Zn(NO_3)_2.6H_2O]$	0.22 M	Spherical shape	[68]

	(Milk thistle)	Silybin A and B					
9.	*Syzygium cumini* (Jamun)	Anthocyanins, Ellagic acid, Flavonoids (Isoquercetin, Kaempferol, Myricetin)	50-60	$[Zn(CH_3COO)_2.2H_2O]$	1 mM	Spherical shape Calcination Temp: 450 °C Time: 3 hours	[69]

2.6. Plant fruit used for the synthesis of ZnO nanoparticles

Several species of fruit have been employed to create ZnO nanoparticles; a few of these are included in Table 6 like *Artocarpus gomezianus, Averrhoe carambola, Borassus flabellifer, Capparis spinosa* L., *Capsicum chinense, Citrus aurantiifolia, Myrica esculenta, Myristica fragrans, Opuntia humifusa, Rosa canina, Solanum lycopersicum, Solanum tuberosum,* and *Ziziphus jujuba* which consist of reducing agents like Jacalin (lectin), flavonoids (Rutin, Quercetin), flavones and quinones, alkaloids (Capparisine A, Capparisine B, Capparisine C), Vitamin A and C, citric acid, maleic acid and ascorbic acid, catechin, myristic acid and myristicin, phenolic acids (Ferulic acid and Protocatechuic acid), phenolic compounds (Proanthocyanidin), Carotenoids (Lycopene), amylopectin and amylose, and phenolic acid (Chlorogenic acid) respectively, showing different morphologies like spherical shape, nanoflake like shape, rod-like shape, pallet-like shape, hexagonal shape, quasi-spherical shape, and non-spherical shape and the particle size distribution from 13 nm to 55 nm [70-82].

Table 6. Plant fruit used for the synthesis of ZnO nanoparticles

Sr. No.	Plant Name	Reducing Agents Identified	Size (nm)	Precursor used	Precursor Concentration	Specifications	Reference
1.	*Artocarpus gomezianus* (Mon-jack)	Jacalin (lectin), Phenolic compounds, Stilbenoids, Aryl benzofurons, Flavonoids	20	$[Zn(NO_3)_3.6H_2O]$	1.6 M	Spherical shape Calcination Temp: 400 °C Time: 4 minutes	[70]

2.	*Averrhoe carambola* (Star fruit)	Phenolic acids, Flavonoids (Rutin, Quercetin), Ascorbic acid, Citric acid, Malic acid	20	$[Zn(NO_3)_2.6H_2O]$	0.5 M	Nanoflake-like morphology Calcination Temp: 400 °C	[71]
3.	*Borassus flabellifer* (Palmyra palm)	Terpenoids, Ketones, Aldehydes, Amides, Flavones, Quinones, Carboxylic acids, Organic acids	55	$[Zn(NO_3)_2.6H_2O]$	0.2 M	Rod-like shape	[72]
4.	*Capparis spinosa* L. (Flinders rose)	Flavonoids (Rutin, Quercetin, Tetrahydroquinoline acid), and Alkaloids (Capparisine A, Capparisine B, Capparisine C)	37.49	$[Zn(CH_3COO)_2.2H_2O]$	0.46 M	Spherical shape	[73]

5.	*Capsicum chinense* (Orange habanero pepper)	Vitamin A and C, Capsaicin, Flavonoids, Carotenoids (Zeaxanthin, Lutein, β-carotene), Phenolic acids	24	$[Zn(CH_3COO)_2.2H_2O]$	1 M	Spherical shape Calcination Temp: 350 °C Time: 2 hours	[74]
6.	*Citrus aurantiifolia* (Lime)	Citric acid, Maleic acid, Ascorbic acid	20-30	$[Zn(CH_3COO)_2.2H_2O]$	0.46 M	Spherical shape Calcination Temp: 310 °C Time: 2 hours	[75]
7.	*Myrica esculenta* (Kaphal)	Catechin, Gallic acid, Ellagic acid, Caffeic acid, 2-Furan carboxaldehyde, Ascorbic acid, Myricetin, Valine, Tyrosine	31.67	$[Zn(CH_3COO)_2.2H_2O]$	0.5 M	Pallet-like morphology	[76]
8.	*Myristica fragrans* (Nutmeg)	Trimyristin, Myristic acid, Myristicin, Safrole, D-pinene,	43–83	$[Zn(NO_3)_2.6H_2O]$	0.2 M	Spherical and hexagonal shapes Calcination Temp: 500 °C Time: 2 hours	[77]

		Myristin, Elemicin					
9.	*Opuntia humifusa* (Indian fig)	Phenolic acids (Ferulic acid and Protocatechuic acid), Flavonoids (Taxifolin, Myricetin, Betanin), Tannins, Saponins	25	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Rod-like shape Calcination Temp: 400 °C Time: 2 hours	[78]
10.	*Rosa canina* (rosehip fruit)	Phenolic compounds (Proanthocyanidin), Phenolic acid, Tannins, Flavonoids, Carotenoids, Fruit acids, Pectin (Citric acid, Ascorbic acid, Malic acid)	13.3	$[Zn(NO_3)_2.6H_2O]$	0.5 mM	Spherical shape Calcination Temp: 400 °C Time: 4 hours	[79]
11.	*Solanum lycopersicum* (Tomato)	Carotenoids (Lycopene), Polyphenols (Flavanones, Anthocyanidi	39 ± 1.2	$[Zn(NO_3)_2.6H_2O]$	1.59 M	Quasi-spherical shape Calcination Temp: 600 °C	[80]

		ns), Ascorbic acid, Folic acid, Citric acid				Time: 3 hours	
12.	*Solanum tuberosum* (Potato)	Starch consists of Amylopectin and Amylose	20 ± 1.2	[$Zn(NO_3)_2.6H_2O$]	0.2 M	Hexagonal in shape Calcination Temp: 500 ℃ Time: 10 minutes	[81]
13.	*Ziziphus jujuba* (Chinese jujube)	Flavonoids (Rutin, Quercetin, Epicatechin, Procyanidins), Phenolic acids (Gallic acid, Caffeic acid, Chlorogenic acid), Vitamin C (Ascorbic acid)	19	[$Zn(NO_3)_2.6H_2O$]	0.05 M	Non-spherical shape Calcination Temp: 500 ℃ Time: 3 hours	[82]

2.7. Plant fruit peel used for the synthesis of ZnO nanoparticles

Various varieties of fruit peels can be used to produce ZnO nanoparticles, some of which are listed in Table 7 like *Ananas comosus, Citrus aurantifolia, Citrus sinensis, Cocos nucifera, Hylocereus polyrhizus, Lycopersicon esculentum, Musa acuminata, Musa paradisiaca, Nephelium lappaceum* L.*, Passiflora foetida,* and *Punica granatum* which consist of reducing agents like Vitamin C and Vitamin B complex, limonoids, polymethoxylated flavones, polyphenols (Tannin, Hydroxybenzoic acid, Ferulic acid), pectin, carotenoids, proteins, biogenic amines, phenolic compounds (Ellagic acid, Corilagin, Geraniin, Ellagitannins) and flavonoids (Apigenin, Luteolin, Quercetin) respectively, showing different morphologies like flower-like shape, pyramid-like shape, hexagonal prism shape, hexagonal bipyramidal shape, spherical shape, round shape, and triangular shape, and have a particle size ranging from 9 nm - 65 nm [83-93].

Table 7. Plant fruit peel used for the synthesis of ZnO nanoparticles

Sr. No.	**Plant Name**	**Reducing Agents**	**Size (nm)**	**Precursor used**	**Precursor Concentration**	**Specifications**	**Reference**
1.	*Ananas comosus* (Pineapple)	Phenolic compounds (Gallic acid, Chlorogenic acid), Flavonoids (Rutin, Quercetin), Vitamin C and Vitamin B complex, Citric acid, Malic acid, Tannins, Saponins, Pectin	64.61	$[Zn(NO_3)_2.6H_2O]$	0.06 M	Flower-like morphology	[83]
2.	*Citrus aurantifolia* (Lime)	Carotenoids, Coumarins, Limonoids, Flavonoids	35-45	$[Zn(CH_3COO)_2.2H_2O]$	0.46 M	Pyramid-like morphology Calcination Temp: 400 °C Time: 15 minutes	[84]
3.	*Citrus sinensis*	Carotenoids, Limonoids,	12-25	$[Zn(NO_3)_2.6H_2O]$	0.2 M	Hexagonal prisms with	[85]

	(Orange)	Vitamin C, and Polymethoxylated flavones,				rounded down corners and oval sphere-shaped Calcination Temp: 400 °C Time: 1 hr	
4.	*Cocos nucifera* (Coconut Coir)	Polyphenols (Tannin, Hydroxybenzoic acid, Ferulic acid, etc.)	48	[$Zn(NO_3)_2.6H_2O$]	0.1 M	Hexagonal Bipyramid in shape Calcination Temp: 400 °C Time: 3 hours	[86]
5.	*Hylocereus polyrhizus* (Dragonfruit)	Triterpenoids, Betanin, Phyllocactin, pectin, Hylocerenin, Betacyanin	56	[$Zn(NO_3)_2.6H_2O$]	0.5 M	Spherical morphology Calcination Temp: 450 °C Time: 2.5 hours	[87]
6.	*Lycopersicon esculentum* (Tomato)	Flavonoids, Carotenoids, Limonoids	9.01	[$Zn(NO_3)_2.6H_2O$]	0.15 M	Hexagonal and round shapes Calcination Temp: 400 °C Time: 1 hour	[88]
7.	*Musa acuminata* (Banana)	Flavones, Amino acids, Alkaloids, Terpenoids, Enzymes, Polyphenols,	30-80	[$Zn(CH_3COO)_2.2H_2O$]	0.01 M	Triangular shape	[89]

		Carotenoids, Proteins					
8.	*Musa paradisiaca* (Plantain peel)	Tannins, Saponins, Phenolic compounds, Biogenic amines, Carotenoids, Flavonoids	20	$[Zn(CH_3COO)_2.2H_2O]$	2 M	Spherical shape Calcination Temp: 350 °C Time: 2 hours	[90]
9.	*Nephelium lappaceum* L. (Rambutan fruit)	Phenolic compounds (Ellagic acid, Corilagin, Geraniin, Ellagitannins)	25.67	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Spherical shape Calcination Temp: 450 °C Time: 5 minutes	[91]
10.	*Passiflora foetida* (Passionflower)	Flavonoids (Apigenin, Luteolin, Quercetin), Phenolic compounds (Gallic acid, Caffeic acid), Tannins, Passifloricins, Cyanogenic compounds, α-Pyrones	58	$[Zn(NO_3)_2.6H_2O]$	100 mM	Hexagonal morphology Calcination Temp: 400 °C Time: 1 hour	[92]
11.	*Punica granatum*	Flavonoids, Tannins,	10–45	$[Zn(CH_3COO)_2.2H_2O]$	5 mM	Spherical shape	[93]

	(Pomegranate)	Anthocyanidins, Phenolic acids				Calcination Temp: 200 °C Time: 3 hours	

2.8. Bacteria used for the synthesis of ZnO nanoparticles

A list of a few bacteria employed in the synthesis of ZnO nanoparticles may be found in Table 8, like *Bacillus cereus* MN181367, *Bacillus licheniformis* MTCC 9555, *Halomonas elongata, Lactobacillus plantarum* TA4, *Lactobacillus sporogens, and Marinobacter sp.* 2C8, *Pseudomonas aeruginosa, Pseudomonas putida* (MCC 2989), *Serratia ureilytica,* and *Streptomyces enissocaesilis* have particle sizes ranging from 2 nm - 360 nm and have different morphologies like irregular shape, hexagonal shape, and spherical shape [94-103].

Table 8. Bacteria used for the synthesis of ZnO nanoparticles

Sr. No.	Biological source	Size (nm)	Precursor used	Precursor Concentration	Specifications	References
1.	*Bacillus cereus* MN181367	58.77-63.3	[$ZnSO_4 \cdot 7H_2O$]	0.01M	Irregular shape	[94]
2.	*Bacillus licheniformis* MTCC 9555	2000-1000	[$Zn(CH_3COO)_2.2H_2O$]	0.2 M	Hexagonal shape	[95]
3.	*Halomonas elongata*	10–27	[$ZnCl_2$]	0.001-0.1 M	Spherical morphology	[96]
4.	*Lactobacillus plantarum* TA4	291.1	[$Zn(NO_3)_2.6H_2O$]	100-500 mM	Flower-like to irregular shape	[97]
5.	*Lactobacillus sporogens*	5–15	[$ZnCl_2$]	0.25 M	Hexagonal shape	[98]
6.	*Marinobacter* sp. 2C8	2.48-10.23	($ZnSO_4 \cdot H_2O$)	0.1 M	Spherical shape	[99]
7.	*Pseudomonas aeruginosa*	27	[$Zn(NO_3)_2.6H_2O$]	1 mM	Spherical morphology	[100]
8.	*Pseudomonas putida*	44.5	[$Zn(NO_3)_2.6H_2O$]	0.0045 M	Spherical shape	[101]

	(MCC 2989)				Calcination Temp: 400 °C Time: 2 hours	
9.	*Serratia ureilytica*	185-360	$[Zn(CH_3COO)_2.2H_2O]$	0.02 M	Hexagonal morphology	[102]
10.	*Streptomyces enissocaesilis*	5-20	$ZnSO_4$	5 mM	Spherical shape	[103]

2.9. Algae used for the synthesis of ZnO nanoparticles

A few algae that are utilized to generate ZnO nanoparticles are listed in Table 9, like *Agathosma betulina, Chlamydomonas reinhardtii, Gracilaria edulis, Gracilaria gracilis, Sargassum muticum, Sargassum myriocystum, Sargassum wightii, Spirogyra hyalina, Ulva fasciata,* and *Ulva Lactuca,* having particle sizes ranging from 10 nm - 80 nm and have different morphologies like quasi-spherical shape, flower-like shape, rod-like shape, hexagonal shape, and spherical shape [104-113].

Table 9. Algae used for the synthesis of ZnO nanoparticles

Sr. No.	**Biological source**	**Size (nm)**	**Precursor used**	**Precursor Concentration**	**Specifications**	**References**
1.	*Agathosma betulina*	15.8	$[Zn(NO_3)_2.6H_2O]$	0.2 M	Quasi-spherical shape Calcination Temp: 100–500 °C Time:2 hours	[104]
2.	*Chlamydomonas reinhardtii*	55-80	$[Zn(CH_3COO)_2.2H_2O]$	1 mM	Flower-like morphology	[105]
3.	*Gracilaria edulis*	65-95	$[Zn(NO_3)_2.6H_2O]$	1 mM	Rod-shape	[106]
4.	*Gracilaria gracilis*	18-50	$[Zn(NO_3)_2.6H_2O]$	0.1 M	Hexagonal shape Calcination Temp: 600 °C Time: 3 hours	[107]

5.	*Sargassum muticum*	30-57	$[Zn(CH_3COO)_2.2H_2O]$	2 mM	Calcination Temp: 450 °C Time: 4 hours	[108]
6.	*Sargassum myriocystum* (Seaweed)	36	$[Zn(NO_3)26H2O]$	1mM	Spherical and hexagonal shapes	[109]
7.	*Sargassum wightii*	20-62	$[Zn(NO3)_2.6H_2O]$	0.05 mM	Spherical shape Calcination Temp: 400 °C Time: 1 hour	[110]
8.	*Spirogyra hyalina*	40-65	$[Zn(CH_3COO)_2.2H_2O]$ OR $[Zn(NO_3)_2.6H_2O]$	0.02 M	Spherical shape Calcination Temp: 455 °C Time: 4 hours	[111]
9.	*Ulva fasciata*	77.81	$[Zn(CH_3COO)_2.2H_2O]$	10 mM	Spherical	[112]
10.	*Ulva Lactuca* (Seaweed)	10–50	$[Zn(CH_3COO)_2.2H_2O]$	1 mM	Hexagonal shape Calcination Temp: 450 °C Time: 4 hours	[113]

2.10. Fungi used for the synthesis of ZnO nanoparticles

Table 10 includes a selection of fungi employed in the fabrication of ZnO nanoparticles, like *Aspergillus fumigatus, Aspargillus niger, Cochliobolus geniculatus, Cordyceps militaris,* and *Fusarium keratoplasticum* strain A1-3 having particle size ranging from 0.17 nm - 42 nm, and have different morphologies like spherical shape, hexagonal shape and quasi-spherical shape [114-118].

Table 10. Fungi used for the synthesis of ZnO nanoparticles

Sr. No.	Biological source	Size (nm)	Precursor used	Precursor Concentration	Specifications	References

1.	*Aspergillus fumigatus* (Extracellular secretion)	1.2-8.56	$[Zn(NO_3)_2.6H_2O]$	0.1 mM	Spherical morphology	[114]
2.	*Aspargillus niger*	40	$[ZnCl_2]$	0.3 M	Hexagonal shape Calcination Temp: 550 °C Time: 3 hours	[115]
3.	*Cochliobolus geniculatus* (Protein)	0.17-0.24	$[Zn(CH_3COO)_2.2H_2O]$	1 mM	Quasi-spherical and hexagonal morphology	[116]
4.	*Cordyceps militaris*	10.15	$[Zn(NO_3)_2.6H_2O]$	0.1 mM	Hexagonal shape	[117]
5.	*Fusarium keratoplasticum* strain A1-3	10-42	$Zn(CH_3COO)_2.2H_2O$	2 mM	Hexagonal shape	[118]

2.11. Mechanism of Green Synthesis

When the zinc metal ion from the zinc precursor reacts with phytochemicals in the plant concentrate, including nimbin, quercetin, ascorbic acid, gallic acid, caffeine, quinine, etc., the zinc metal ions are reduced. The metal ions are decreased by plant extracts and then stabilized by an organic covering. Zinc oxide is created when zinc metal ions are exposed to phytochemicals. The fabrication of metallic nanoparticles from phytochemical concentrate proceeds through activation—bio reduction and nucleation of metal ions, followed by a growth state involving particle aggregation, and terminates with termination, which finalizes the shape of the nanoparticle. The sample is subsequently calcined at a high temperature to eliminate any remaining impurities, resulting in purified ZnO nanoparticles. Figure 5 describes the mechanism of the green synthesis method for creating ZnO nanoparticles [119].

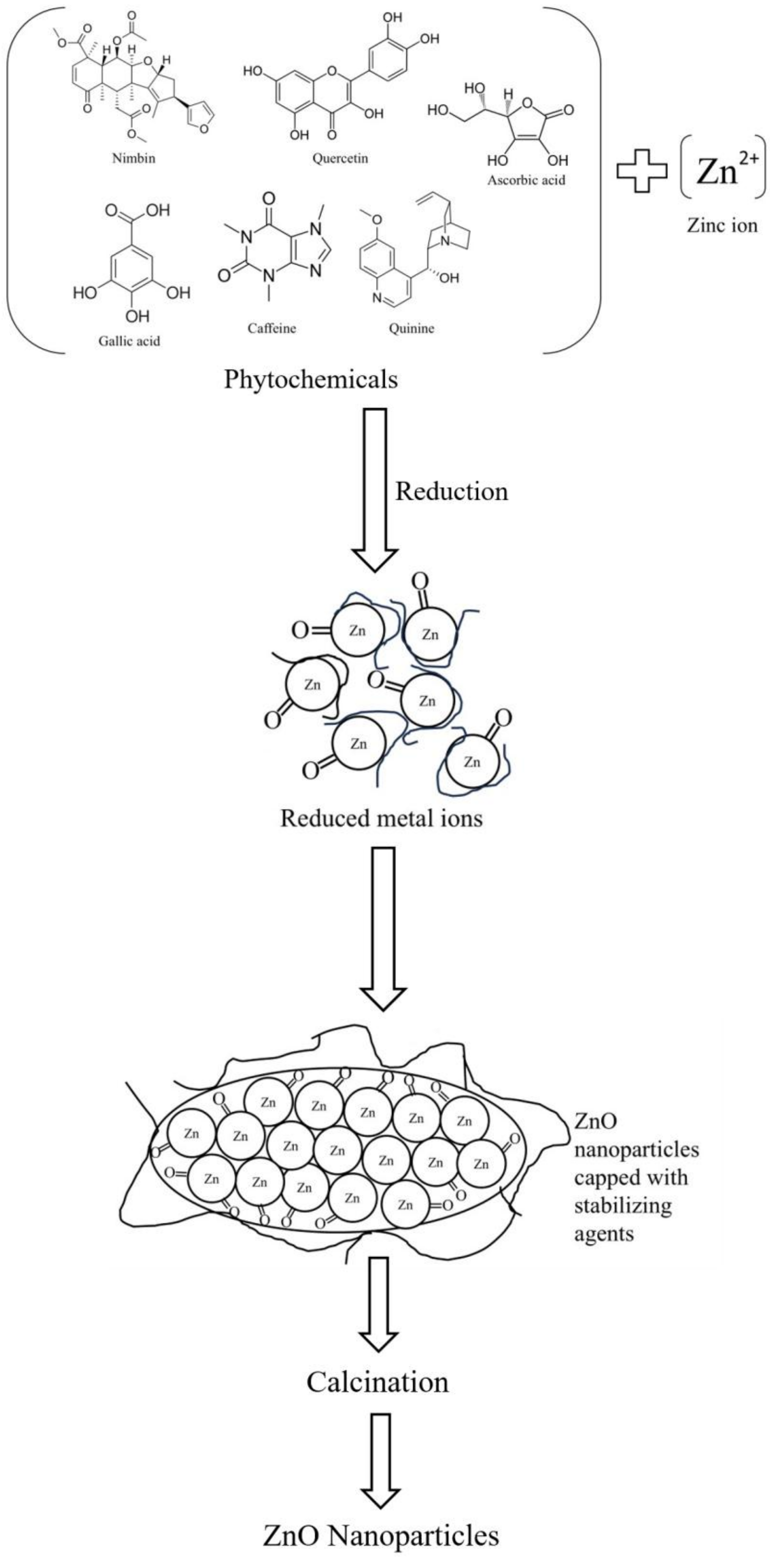

Figure 5. Green synthesis mechanism for the fabrication of ZnO nanoparticles

2.12. Conclusion

The fabrication of ZnO nanoparticles with extracts from plants, algae, fungi, and bacteria has emerged as a feasible method for creating eco-friendly nanomaterials with improved functional properties and biocompatibility. This method eliminates the need for harmful chemicals commonly employed in traditional synthesis pathways by using naturally occurring phytochemicals such as flavonoids, proteins, polyphenols, and polysaccharides for reduction and stabilization. Plant extracts' rich phytochemical makeup has demonstrated tremendous potential in aiding the production of nanoparticles of certain sizes and forms. Likewise, the physiologically active metabolites that give ZnO nanoparticles their distinct physicochemical characteristics are advantageous for production by algae. The durability of nanoparticles is further improved by bacterial and fungal extracts through the release of biomolecules, providing an alternate method that aids in the production of sustainable materials. Bio-mediated synthesis substantially decreases energy consumption, reduces environmental toxicity, and enables the production of ZnO nanoparticles with improved surface characteristics suitable for environmental remediation, biomedicine, and catalysis.

The improved antibacterial, anti-inflammatory, and antioxidant qualities of biosynthesized ZnO nanoparticles make them attractive options for drug delivery and wound healing applications. Despite these advantages, challenges remain regarding the standardization of synthesis procedures, the reproducibility of nanoparticle properties, and the scalability for industrial applications. Understanding the basic processes underlying the synthesis of biological nanoparticles, improving synthesis conditions, and investigating hybrid approaches that combine traditional and bio-inspired techniques are all crucial to the advancement of this technology.

In the realm of green synthesis of ZnO nanoparticles, numerous research publications and reviews have been released; however, this field still lacks sufficient research. One notable observation is the chemical analysis of plant extracts. Although GC-MS analysis has provided insights into the chemical composition of various plant extracts, no specific information has been available regarding which particular chemical compound or molecule acts as a reductant and particle stabilizer.

In conclusion, zinc oxide nanomaterials produced by using biological extracts align with sustainable practices and offer a practical means of producing valuable nanomaterials with minimal environmental impact. Increased multidisciplinary research will pave the way for applying bio-mediated nanoparticle synthesis across diverse domains, such as environmental science and healthcare, unlocking innovative, environmentally responsible nanotechnology solutions.

3. MATERIALS AND METHODS

3.1. Introduction

Numerous physical and chemical methods covered here are capable of generating nanomaterials of diverse morphologies and sizes, but they are time-consuming, require expensive equipment, hazardous chemicals, non-biodegradable stabilizing agents, and hazardous organic solvents. Consequently, it is essential to develop a simple, safe, and sustainable method for producing ZnO nanoparticles [120]. With biological synthesis, more nanoparticles could be produced without the harsh, costly, and hazardous chemicals typically utilized in traditional physical and chemical processes [121]. Many substances, such as terpenoids, vitamins, amino acids, alkaloids, phenolic compounds, and nitrogen compounds, are known to scavenge free radicals. Antioxidants and polyols, which are abundant in these plants, are used to make nanoparticles [122]. Plants are the best source of feedstock for making metal oxide nanoparticles because they can easily transform metal salts or ions into zero-valence metal nanoparticles [123]. Furthermore, compared to nanoparticles created by physical or chemical means, those derived from phytochemical concentrate are highly robust and biocompatible. The rapid reduction and stabilizing agents for the produced nanoparticles are thought to be caused by the secondary metabolites found in plant extracts [124]. Additionally, plant-based biosynthesis is a rather simple procedure that may easily be expanded to create nanoparticles on a large scale [125].

One way to summarize the basic experimental procedure for creating eco-friendly nanoparticles is as follows: Before the leaves of the plant are utilized in an experiment, they are properly cleaned under running water multiple times and dried. Following drying, the leaves were ground into a powder and kept at low temperatures in an airtight container. Any leftover bulk material was eliminated by filtering, centrifuging, and mixing the powdered leaves with distilled water at a steady temperature [126]. The flowers of the plant are washed several times if they are being used in order to stay clear of foreign things. Deionized water is used as part of a routine cleaning procedure after the flower has been dried and ground into a powder. The extract was created by filtering, centrifuging, and heating the mixture while swirling it with a magnetic stirrer at a constant temperature [127]. This implies that any plant material utilized to create ZnO nanostructures must first undergo a comparable series of preparatory steps for purification and concentration before being combined with the zinc ion source [128].

3.2. Procedure Followed for Green Synthesis

An outline of the green synthesis method employed to create ZnO nanoparticles is shown in Figure 6. According to the figure, any plant component, be it peel, root, stem, leaf, or fruit, is combined with a zinc source like zinc sulphate, zinc nitrate, zinc acetate, or zinc chloride. The plant material was boiled with distilled water to create the plant extract, and the zinc source was mixed in distilled water and used as a solvent. Plant extract was added to this zinc precursor solution while it was being stirred, and then a gentle addition of NaOH solution. After filtering and drying in an oven for the entire night, a zinc hydroxide precipitate was seen. In order to obtain the ZnO nanoparticles, the dried precipitate was first finely crushed, calcined at a high temperature, and then powdered.

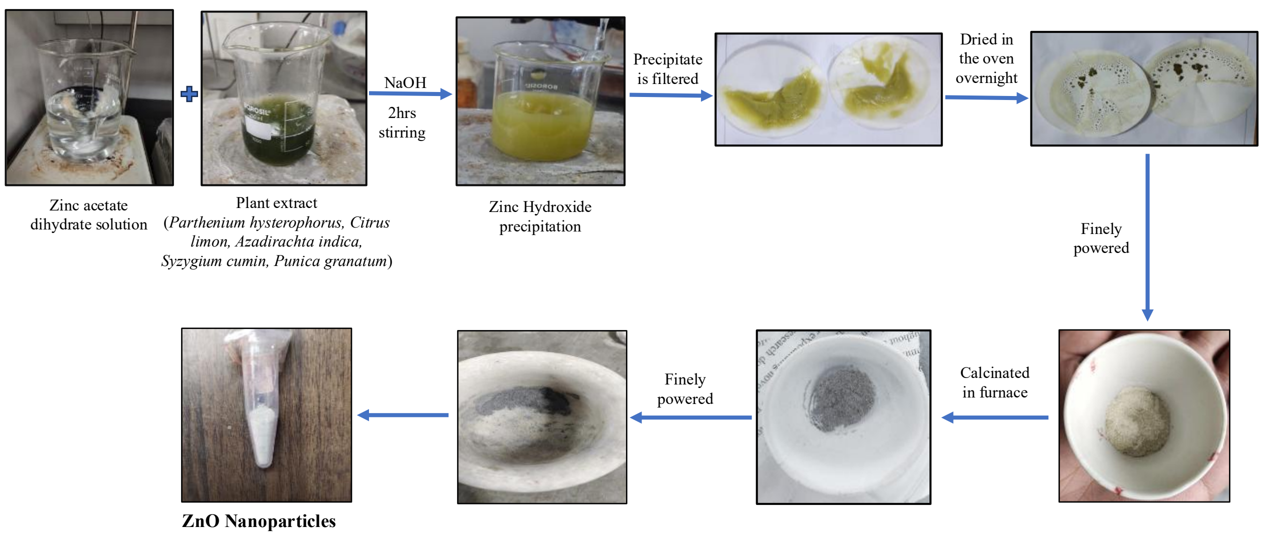

Figure 6. Illustration of the green synthesis process for synthesizing ZnO nanoparticles

3.3. Materials & Methods

The leaves of *Parthenium hysterophorus, Citrus limon, Azadirachta indica, Syzygium cumin, and Punica granatum* were collected from the campus of Delhi Technological University. Zinc acetate dihydrate was purchased from SRL. Other chemicals like sodium hydroxide, acetone, methanol, and distilled water were utilized from the laboratory of the science department of Delhi Technological University. Nano characterization methods, namely UV-Visible spectroscopy, Zeta sizer, and Zeta potential, were done at the Delhi Technological University.

Following collection, the leaves were thoroughly rinsed under running water to remove impurities, then placed in a hot air oven at 60 °C for three days prior to their use. The dried leaves were manually crushed using a mortar and pestle and stored in a sealed container. The powdered leaves were then mixed with distilled water at a consistent temperature of 60 °C for 30 minutes. The resulting concentrate was then filtered and refrigerated for further use. Different concentrations of zinc acetate solutions (1 M, 2 M, 3 M, etc) were prepared by weighing the zinc acetate powder on a weighing balance and dissolving it in distilled water on a stirrer at a constant temperature of 60 °C for a few minutes. Subsequently, NaOH solution was prepared. To the zinc acetate solution, plant extract was added while on the stirrer and allowed to mix homogenously for a few minutes. After adding the NaOH solution gradually, the reaction solution was continuously agitated for two hours at 60 °C. Overnight filtration was done on the resulting precipitate, and dried for 24 hours in an oven after the reaction was finished. The dried precipitate was then finely powdered and calcinated in the muffle furnace. After calcination, it was again finely powdered, which resulted in ZnO nanoparticle powder.

4. RESULTS AND DISCUSSION

4.1. UV-Visible Spectroscopy

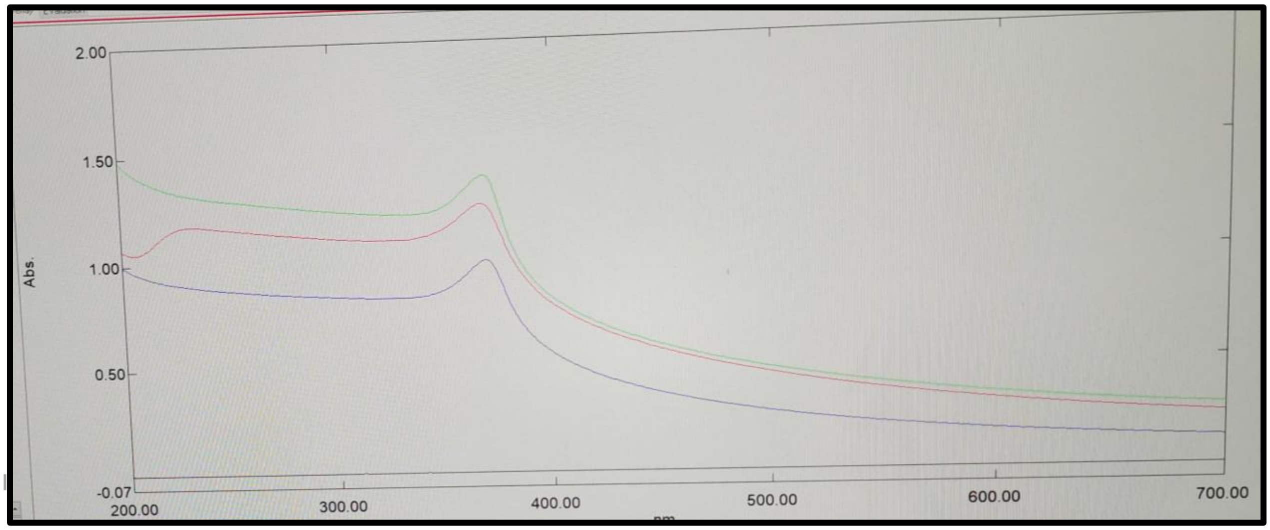

Figure 7. UV-Visible graph of one of the samples of ZnO nanoparticles synthesized using leaves of *Parthenium hysterophorus*

Figure 7 demonstrates the UV-Visible peaks of sample having the best results. The UV-Vis of ZnO samples were noted for 1 M, 2 M, and 3 M concentrations. UV-Vis absorbance peak for ZnO ranges from 300 to 400 nm. From the graph, it was observed that the highest absorbance was at 364.22 nm for 1 M and 2 M concentrations, and 372.42 nm for 3 M concentration.

4.2. Zeta Sizer & Zeta Potential

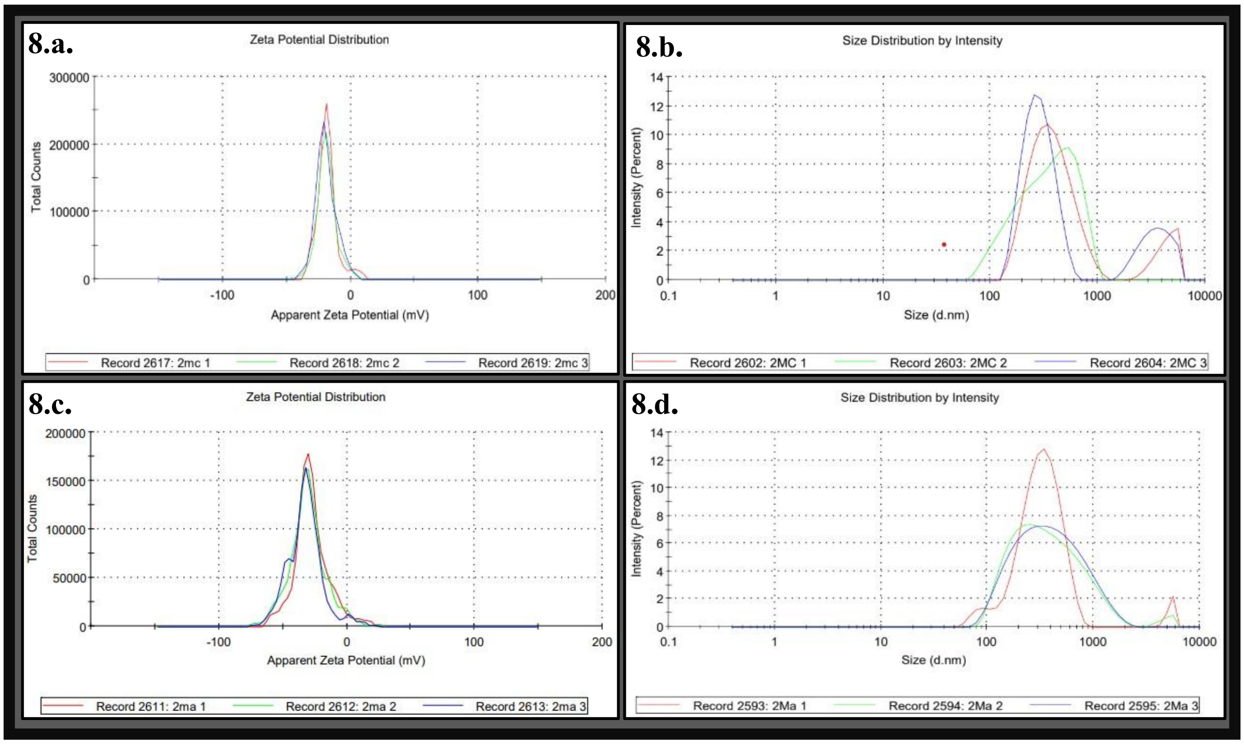

Figure 8. Zeta sizer and zeta potential of ZnO nanoparticles at 2 M concentration, synthesized using leaves of *Parthenium hysterophorus*

The zeta sizer and zeta potential of ZnO nanoparticles prepared at 2 M concentration using leaves of *Parthenium hysterophorus* are shown in Figure 8. The samples were prepared at two different concentrations (w/v). Graphs 8.a and 8.b show the zeta potential and zeta sizer at 0.6 % concentration (w/v). The average zeta potential observed in graph 8.a is -19.2 mV, and the zeta size distribution observed in graph 8.b shows the average size 342.1 d.nm. Graphs 8.c and 8.d show the zeta potential and zeta sizer at 0.3 % concentration (w/v). The average zeta potential observed in graph 8.c is -32.5 mV, and the zeta size distribution observed in graph 8.d shows the average size 299.5 d.nm. These were the best results that were observed so far.

4.3. Summarization of the Experiments Performed

Table 11 gives a comprehensive summary of the outcomes of all the experiments conducted during the study.

Table 11. Experiments performed and their observations

Sr. No.	Plant extract	Precursor	NaOH/ Buffer solution	Calcination	Observations
1.	Water-based plant extract (3g in 30 ml)	Zinc acetate (0.1M)	NaOH (1M)	For 3hrs at 300°C	ZnO NPs did not form as there was no absorbance peak observed in UV-Vis spectroscopy
2.	Water-based plant extract (20g in 100 ml)	Zinc acetate 9 samples (3 each of 1:1, 1:2, 2:1)	NaOH (1M)	Each sample for 3hrs at 300°C	ZnO NPs formed with a size range of 3000-5000nm
3.	Water-based plant extract (20g in 100 ml)	Zinc acetate (1M,2M,3M)	NaOH (1M)	Each sample for 3hrs at 300°C	ZnO NPs formed with a size distribution of 299-3085 nm (Sample 2 (2M) - 299.5nm)
4.	Water-based plant extract (20g in 100 ml)	Zinc acetate (2M)	PBS Buffer solution (pH = 8.5, 12.5)	N/A	A viscous liquid formed
5.	Water-based plant extract (20g in 100 ml)	Zinc acetate (2M)	NaOH (1M)	3 Samples made calcined for 1hr, 2hr, 3hr at 300°C	ZnO NPs formed with a size range of 2106-5257nm
6.	Water-based plant extract *of Citrus limon* (lemon), *Azadirachta indica* (neem),	Zinc acetate (2M)	NaOH (1M)	Each sample for 3hr at 300°C	ZnO NPs formed with a size range of 3647-6553nm (Parthenium- 3647nm)

	Syzygium cumini (jamun), *Punica granatum* (pomegranate), *Parthenium hysterophorus* (congress grass)				
7.	Water-based plant extract (20g in 100 ml)	Zinc acetate (2M)	NaOH (1M)	3 Samples made calcined for 1hr, 2hr, 3hr at 300°C	ZnO NPs formed with a size range of 2106-5257nm

4.4. Conclusion

In this study, water-based leaf extracts of Parthenium hysterophorus (congress grass), Citrus limon (lemon), Azadirachta indica (neem), Syzygium cumini (jamun), and Punica granatum (pomegranate) were used to create ZnO nanoparticles. Following a number of syntheses, it was found that the Parthenium hysterophorus (congress grass) leaf extract produced at a 2 M concentration produced the best results. At 364.22 nm, it displayed the maximum UV-visible absorption. The zeta size distribution revealed the smallest average size, 299.5 d.nm, and the best average zeta potential was -19.2 mV. Various parameters, such as zinc acetate and plant extract concentration, calcination temperature, and reaction time, were altered and adjusted in this study to investigate their influence on ZnO nanoparticle fabrication.

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