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REVIEW ARTICLE

A REVIEW OF SUSTAINABLE METHODS FOR SYNTHESIZING ZINC OXIDE NANOPARTICLES AND THEIR APPLICATIONS

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ABSTRACT

Zinc oxide (ZnO) nanoparticles are versatile materials with broad applications due to their unique properties. This review examines the synthesis methods of ZnO nanoparticles, including sol-gel, microwave- assisted, and green synthesis. The sol-gel method allows precise control over particle size and morphology, while microwave-assisted synthesis offers rapid, uniform particle formation. Green synthesis uses plant extracts for eco-friendly production. Characterization techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR) reveal the structural and morphological properties of the synthesized nanoparticles. Applications of ZnO nanoparticles in antifouling coatings, biomedical fields (antibacterial and anticancer), and energy systems are discussed. The review evaluates each synthesis method's efficiency, scalability, and environmental impact, highlighting their potential for sustainable applications.

KEYWORDS

Plan extract, Microorganisms, ZnO NPs, Eco-friendliness, Environmental remediation.

1. INTRODUCTION

The synthesis of nanoparticles by living cells via biological processes is the subject of the newly developing scientific field known as "green nanotechnology" (Vijayaram et al., 2024). This subject is crucial to several industries, such as biotechnology, electronics, nuclear energy, fuel and energy, and medicines. Because biological procedures using green synthesis tools are safer, more environmentally friendly, non-toxic, and more economical than other similar approaches, they are better suited to produce nanoparticles between 1 and 100 nm. When compared to other analogous approaches, the green synthesis of nanoparticles employing live cells and biological pathways is more efficient and yields a larger mass (Youssef et al., 2024). Many of the components and biochemicals needed to create green nanoparticles can be found in plants, and they can also act as reducing and stabilizing agents. When compared to alternative biological, physical, and chemical procedures, the green synthesized technologies are more durable, non-toxic, economical, and environmentally friendly (Osman et al., 2024). The three categories of green nanoparticle synthesis are phytochemicals, extracellular, and intracellular. Because there are so many phytochemical components in plant extract—which may also function as stabilizing and reducing agents to convert metal ions into metal nanoparticles—the technique of synthesizing nanoparticles from plant extract is less expensive and yields higher outcomes (Vijayaram et al., 2024).

1.1 ZnO Nanoparticles

Zinc oxide nanoparticles, or ZnO NPs, are extremely desirable in a variety of industries due to their unique properties. However, hazardous materials used in current ZnO-NPs production methods pose a risk to human health and the environment (Bhattacharjee et al., 2024). We examine in fully the synthesis of zinc oxide nanoparticles (ZnO NPs) from plant extracts and their subsequent applications in biomedicine in this review. Studies reveal that a variety of plant extracts are used in the production of ZnO nanoparticles. These extracts contain leaves, fruits, seeds, roots, even entire plants. These biological matrices include phytochemicals including flavonoids, terpenoids, alkaloids, and phenolic compounds. Compounds that exhibit a bio reduction process serve as reducing and stabilizing agents. ZnO nanoparticles produced sustainably have a wide range of applications in medicine, including antibacterial activity against a variety of pathogens, anti-inflammatory properties, and potential anticancer properties. Nanoparticles have been introduced to wound dressings, employed as drug delivery vehicles, and used in imaging and bio sensing applications (Prashanth, et al., 2024). When compared to conventional methods, green-processed zinc oxide nanoparticles (ZnO NPs) have greater biocompatibility and less toxicity, which makes them highly desirable for application in biomedical settings (Al-darwesh., 2024).

1.2 Heavy Metals and Their Toxicity

A group of metallic elements known for their high density, atomic weight, and possible danger to human health are commonly used to classify heavy metals. Even though very small quantities of some heavy metals—such as co, which is a component of vitamin B12—are necessary for life, prolonged or excessive exposure to some heavy metals can have adverse impacts on a number of physiological systems (Kamari et al., 2024). It is interesting to note that the phrase "heavy metals" has been defined in a variety of ways in scientific literature. For example, metalloids like the non-metals As and Se have been included in the definition of "heavy metals," which is now defined as "naturally occurring metals having an atomic number greater than 20 and an elemental density greater than 5 g/ml" (Zhao et al., 2024). A selection of representative metals, including lead, copper, zinc, nickel, cobalt, chromium, and cadmium, has been made from this group in order to explore the possibilities of their biosorption. The metalloid arsenic, which is a highly dangerous pollutant, is the lone exception among the metals taken into consideration. Biosorbents are also examined for its removal (Staszak and Regel-Rosocka, 2024).

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Table 1: Zinc oxide nanoparticles synthesized from different plant and plant part extracts and their significance.				
Plant	**Plant part**	**Shape and Size**	**Applications**	**Reference**
Bryophyllum pinnatum	Leaves	126nm	Photocatalytic degradation of industrial contaminants	(Dhiman and Kondal, 2023)
Brassica oleracea	Leaves	52nm	Environmental and antipathogenic applications	(Manojkumar, 2023)
Lawsonia inermis	Seeds	10nm	Antibacterial	(Bhatt et al., 2023)
Grewia asiatica	Fruit Pulp	29nm	Degradation of industrial wastewater dyes	(Aziz et al., 2023)
Tinospora cordifolia	Roots and Stems	74nm	Degradation of MB dye	(Sharma et al., 2023)
Peltophorum pterocarpum	Fruit	59nm	Antifungal	(Vinayagam et al., 2023
Artocarpus gomezianus	Fruits	59nm	Degradation of MB dye	(Kaur et al., 2023)
Pomegranate granatum	Fruits	156nm	Photoprotective	(Otaviano et al., 2023)
Avicenna marina	Leaves	29.1nm	Removal of toxic metal ions (Cd2+ and Pb2+	(Al-Mur, 2023)
Zingiber officinale	Stems	30-35nm	Antibacterial	(Kebede Urge et al., 2023)

1.3 ZnO Nano Particles and Heavy Metals

The green synthesis of zinc oxide nanoparticles (ZnO-NPs) using plant extracts has drawn a lot of attention recently because of its potential uses in a variety of industries. By doing away with the need for dangerous chemicals and lowering dependency on non-renewable resources, this synthetic approach minimizes dangers to human health and the environment (Obiuto et al., 2024). These ZnO-NPs can be applied to environmental remediation tasks, such treating wastewater or remediating soil, to efficiently remove pollutants and enhance the general health of the ecosystem. With a band gap of 3.2 eV and a high surface area, these nanoparticles may generate both superoxide (O2−°) and hydrogen (OH) radicals for the creation of holes (h+) and electrons (e−). This leads to the oxidation and reduction of pollutants in their valence band (VB) and conduction band (CB) results in the following processes: photo catalysis-induced dye degradation (95–100% of MB, MO, and RhB dyes), reduction and removal of heavy metal ions (Cu^{2+}, Pb^{2+}, Cr^{6+}, etc.), and pharmaceutical drug degradation (acetaminophenone (ciprofloxacin), urea, and paracetamol. Here, we provide a summary of the several plant extracts that are utilized in the environmentally friendly synthesis of ZnO NPs and discuss their possible uses in heavy metal, photo catalysis, and adsorption environmental remediation (Jadoun, et al., 2024).

Table 2: Industrial Sources and Associated Health Effects of Toxic Metals on Human Well-Being.			
Metal	**Industrial source**	**Effects on Human Well-Being**	**Reference**
Arsenic	Mining, smelting, pesticide manufacturing, wood preservatives	Skin lesions, malignancies of the skin, lungs, bladder, liver, and kidney; cardiovascular problems; neurotoxicity; developmental impacts; diabetes.	(Staszak and Regel-Rosocka, 2024; Huang et al., 2024)
Lead	Metallurgical, electroplating, metal finishing industries, manufacturing of paints, storage batteries, petroleum refining and drainage from ore mines	May cause pregnant sickness, increase the risk of lung, stomach, and bladder cancer, harm the kidney, neurological system, reproductive system, liver, and brain, and impede the early stages of fetal development.	(Jagota et al., 2024; Budi et al., 2024)
Mercury	Metal smelting, coal production, waste disposal, and chemical synthesis	Prenatal abnormalities, neurotoxicity and nephrotoxicity, and cognitive impairment in children.	(Wu et al., 2024; Zafar et al., 2024)
Nickel	Alloy production, electroplating, production of nickel–cadmium batteries	Allergy, lung fibrosis, kidney and cardiovascular disorders, lung and nasal cancer.	(Rizwan et al., 2024; Hassan et al., 2024)
Zinc	Electroplating, hot-dip galvanizing, metallurgy, production of batteries, pigments	immune system disorders, prostate issues, diabetes, and macular degeneration.	(Ozoani et al., 2024; Luo et al., 2024)

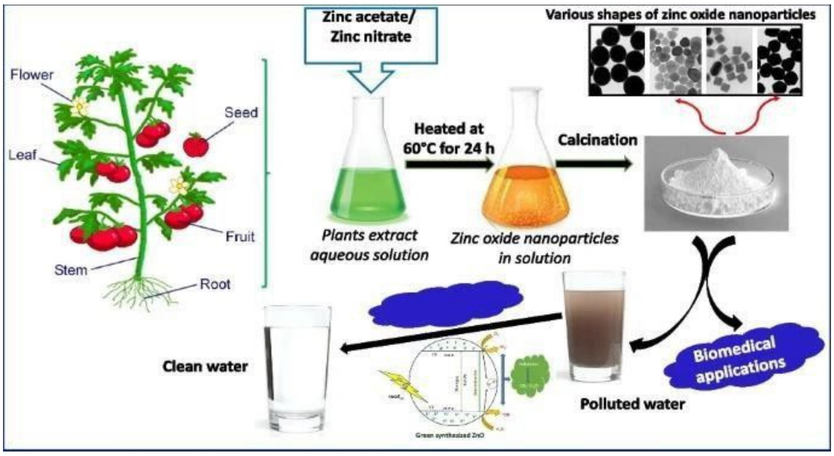

Figure 1: Plant extracts that are utilized in the environmentally friendly synthesis of ZnO NPs.

1.4 Advantages of Green Synthesis

Nanoparticles (NPs) have significant antibacterial activity at low dosages because to their enormous "surface-to-volume" ratio and exceptional, sometimes unique, chemical and physical properties (Jadoun et al., 2024). They also withstand tough environments better, including high temperatures and pressures, and some of them are even safe and contain minerals that are essential to human health (kumar Sahu et al., 2024). Despite the growing usage of NPs in food packaging, issues regarding toxicity and possible health hazards influence consumer adoption and perception. Numerous studies have shown that nanoparticles may move from packaging or containers into food. Nevertheless, a number of experimental investigations have also demonstrated that, in comparison to other migration rates, the quantity of reports of nanomaterial movement and migration is rather low (Lomeli-Martin et al., 2024). This has led to a growing emphasis on "green or environmentally friendly production" of nanomaterials among scientists and producers. Natural resources including microorganisms, plant extracts, bioactive compounds, etc. are used in green synthesis. Green synthesis techniques have several benefits over conventional chemical and physical techniques, including being less costly, simpler to use, safer, devoid of contaminants and dangerous chemicals, renewable, energy-free, and not requiring high pressures or temperatures to function (Al-Salama et al., 2024).

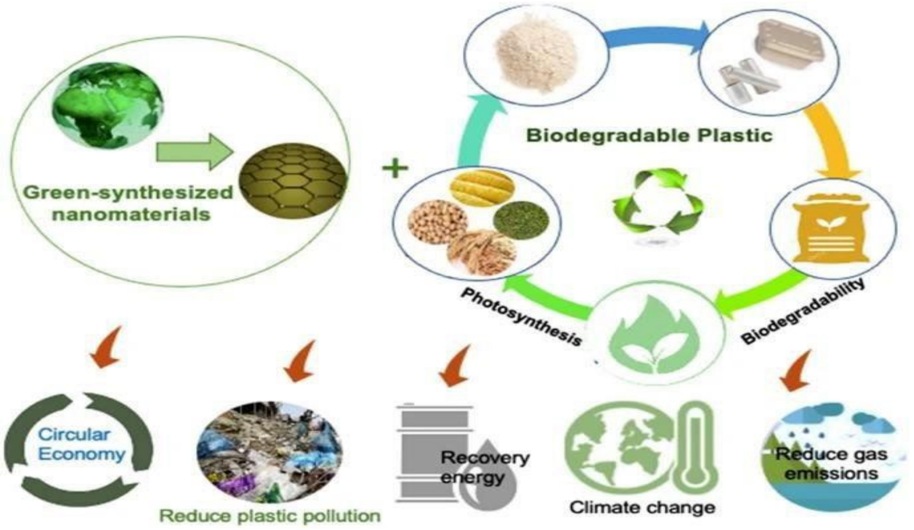

Figure 2: Green synthesis techniques

2. Various Methods of Synthesis

Zinc oxide nanoparticles have been used by several researchers as a medicine delivery method for a variety of diseases (Youssef et al., 2024). For humans, animals, and plants, zinc is regarded as an essential micronutrient. ZnO NPs has been shown to positively impact plant physiology and growth. Nano fertilizers has demonstrated an increase in yield, fruit quality, juice sugars, and maturity index. ZnO NPs are made using a variety of manufacturing methods, including spray pyrolysis, laser ablation technique, physical vapor deposition, microwave assisted method hydrothermal processing, sol-gel, vapor condensation, and thermal hydrolysis etc (Haque et al., 2020). This review focus on hydrothermal process, sol-gel method, microwave assisted method, co-precipitation method, green synthesis, laser ablation technique etc.

2.1 Synthesis by Hydrothermal Process

The hydro-solvothermal approach is one of the primary means of synthesizing distinct ZnO forms among the several ZnO manufacturing procedures because it allows for strict control over the formation of crystallites and relatively simple up-scaling (Ejsmont and Goscianska, 2024). Because it has so many benefits over other approaches, the hydrothermal method stands out as an important method for manufacturing nanoparticles, especially zinc oxide nanoparticles. First of all, compared to techniques requiring high temperatures or sophisticated equipment, it is accessible and affordable due to its simple setup. Its efficiency also makes it an attractive option for researchers, especially when combined with cheap cost and little risk. Ensuring consistent manufacturing on a large scale is made possible by the hydrothermal process, which offers fine control over particle size, morphology, and size distribution. Notably, it meets sustainability objectives because it runs at low temperatures and is eco-friendly. Utilizing the advantages of the hydrothermal method, the researchers in the study under review sought to optimize the properties of zinc oxide nanoparticles by adjusting reaction temperature, precursor molar ratios, alkaline solution concentration, and solvent type. The goal was to produce tiny crystalline particles while preserving energy throughout the synthesis process by methodically examining the impact of these factors on the properties of the generated nanoparticles. To attain precise molar ratios, zinc acetate dihydrate (ZAD) and sodium hydroxide (NaOH) were separately dissolved in deionized distilled water (DDW) during the synthesis procedure. Then, to create a precursor combination, these solutions were combined with methanol, an organic solvent. Zinc hydroxide ($Zn(OH)_2$) precipitate formed as a white slurry when the pH was adjusted by adding the NaOH solution dropwise. The reaction was conducted at various temperatures for a designated period of time following complete mixing and transfer to an autoclave lined with Teflon. After the reaction, the solid product that was produced was gathered, cleaned to get rid of extra ions, and then dried for additional analysis. In order to be identified in ensuing investigations, the nanoparticles that were generated under various circumstances were tagged appropriately. The researchers set out to investigate the effects of temperature, precursor molar ratios, solvent concentration, and shape on the crystalline size, functional groups, energy band gap, morphology, and elemental composition of zinc oxide nanoparticles (Josun et al., 2024).

In this work, zinc oxide (ZnO) nanoparticles were synthesized using a straightforward hydrothermal approach using zinc nitrate ($Zn(NO_3)_2$), zinc acetate ($Zn(CH_3CO_2)_2$), and zinc chloride ($ZnCl_2$) as zinc precursors. The hydrothermal synthesis process was selected because it was less expensive, had less risks, and required lower operating temperatures than alternative approaches. Using magnetic stirring, the appropriate concentrations of each zinc salt were individually dissolved in 50 milliliters of distilled water and a sodium hydroxide (NaOH) solution that was readily available for purchase. After that, these solutions were placed in an autoclave to be processed further. Following synthesis, the resultant powders were air-dried at room temperature and cleaned many times to get rid of contaminants (Bahtoun et al., 2023).

First, deionized water was used to dissolve zinc nitrate and sodium hydroxide to create a solution. Because these substances can supply zinc ions and hydroxide ions, respectively, which are necessary for the synthesis of ZnO nanoparticles, they were selected as precursors. After that, the mixture was vigorously stirred to guarantee that the precursors were evenly mixed. Then, hydrothermal treatment was applied to the homogenous solution. The procedure entails the solution being placed in a Teflon-lined sealed reactor and heated to high pressure and temperature. For the course of 12 hours, the solution in this instance was kept at 180 °C. During this period, a regulated crystallization process between the zinc and hydroxide ions produced zinc oxide nanoparticles. Following the hydrothermal treatment, the reaction mixture-containing autoclave was let to cool naturally to room temperature. ZnO nanoparticles precipitated out of the solution in the form of white precipitates once the reaction was finished. After being carefully gathered, these precipitates were washed to get rid of any remaining contaminants. For washing, deionized water and ethanol were utilized. Ultimately, to eliminate any leftover moisture and guarantee the durability of the cleaned ZnO nanoparticles, they were dried at a temperature as low as 70 °C. The characteristics of nanoparticles can be preserved by preventing agglomeration or sintering via drying at a reasonable temperature. All in all, this meticulous synthesis method produced superior ZnO nanoparticles fit for a range of uses, such as the Hydrogen Evolution Reaction (HER) (Alahmari et al., 2024)

Two distinct hydrothermal techniques, temperature-altered synthesis and pH-altered synthesis were used to synthesize zinc oxide (ZnO) nanoparticles. Zinc acetate dihydrate was dissolved in distilled water for the temperature-altered synthesis. Citric acid and sodium hydroxide solution were then added. The reaction mixture was moved into a steel autoclave lined with Teflon and subjected to hydrothermal treatment for 24 hours at temperatures between 100 and 200 °C. The items underwent filtering, an ethanol and water wash, and a 24-hour drying period at 60 °C. Samples were labeled based on the temperature that was applied. Zinc acetate dihydrate was dissolved in distilled water for the pH-altered synthesis. A sodium hydroxide solution was then added dropwise to correct the pH. A pH meter was used to regulate the pH, and the readings ranged from about 7.5 to 13.5. After being moved inside steel autoclaves coated with Teflon, the reaction solutions underwent a 12-hour hydrothermal treatment at 160 °C. Following treatment, the goods underwent filtering, an ethanol and water wash, and a 24-hour drying process at 60 °C. The samples were assigned numbers based on their modified pH levels. Using these synthesis techniques, ZnO nanoparticles with different properties might be produced, contingent on the pH or temperature during the hydrothermal treatment process (Ejsmont and Goscianska, 2023).

This procedure involves precisely weighing different zinc salts and then combining them with varying volumes of NaOH. Introduction of the salt mixes into a container containing substances like PEG, PEI, TMAH, and HMTA. use a calibrated pH meter to monitor pH and standard solutions to modify pH between 11 and 13.75. Drying of the produced salt combinations at various pH values by the use of ultrasonic, microwave, or air oven drying techniques. In certain tests, NaOH is added gradually at a flow rate of 5 milliliters per minute until the required pH is reached. The combination is centrifuged at a moderate temperature, after which the nanoparticles dissolve in an acidic solution and retreat by hydrothermal precipitation in an alkaline medium. homogenization of the product, which is thereafter placed within an autoclave made of stainless steel and coated with Teflon, and heated to 160°C under autogenous pressure. The final white product, or nanoparticles, are cleaned and dried at 60°C using distilled water. Optimizing the manufacturing of zinc oxide nanoparticles for a range of uses, such as the creation of antibacterial coatings, is the goal of this synthesis procedure (Foudi et al., 2023).

2.2 Synthesis by Sol-Gel Method

For ZnO nanoparticles, a variety of synthesis techniques have recently been used, including the low-temperature hydrothermal method, the sol-gel approach, and chemical solution methods. The sol gel method is the most essential and favored method among the others in terms of cost-effectiveness. Controlling growth and reaction parameters is another advantage of a Sol-gel technique, and it may also help to change the characteristics of nanomaterials. The characteristics and phase structure of nanomaterials are modified during the synthesis process by a variety of factors, including pH level, ambient conditions, and stirring time for solution preparation (Rathore et al., 2024).

This process makes use of the sol-gel technique to create zinc oxide (ZnO) nanoparticles. Materials used include isopropanol, NaOH solution, deionized water, and zinc acetate dihydrate. Firstly, a homogenous solution was created by continuously stirring zinc acetate dihydrate in deionized water. NaOH solution is added dropwise until the pH is around 3. So, until a translucent solution is reached, isopropanol is added gradually. An oven is used for 48 hours to dry this solution after it has been agitated overnight at 100°C. In order to create crystalline ZnO nanoparticles, the dried sample is finally annealed at 350°C for 4 hours in ambient air. An even, crystalline product that may be used in a variety of ways is produced by this procedure (Rathore et al., 2024).

Synthesis of ZnO NPs by this method dissolve 2 grams of zinc acetate dihydrate in 15 milliliters of distilled water. Then, the mixture was stirred constantly until became transparent. To guarantee complete mixing, sonication was then used for ten minutes at room temperature. Ten milliliters of deionized water was mixed with eight grams of sodium hydroxide in parallel. Maintaining a pH of 12 is important when titrating the sodium hydroxide solution slowly into the zinc acetate dihydrate solution. A white precipitate was formed as a result of this. After that, the precipitate was dried for 30 minutes at 100°C and then calcined for 2 hours at 300°C to create pure zinc oxide nanoparticles (Salman and Renuka., 2023).

Zinc oxide (ZnO) nanoparticles were created in the synthesis procedure that was detailed using the sol-gel technique. First, 150 mL of distilled water was used to dissolve 9.7 grams of zinc acetate dihydrate, which was then agitated for 30 minutes at 35°C. Simultaneously, 80 milliliters of deionized water were mixed with 4.5 grams of potassium hydroxide (KOH) and mixed thoroughly. After progressively incorporating the KOH solution into the zinc acetate dihydrate mixture, the mixture was stirred for eight hours to create a gel, which was then allowed to settle for a day at room temperature. After 48 hours of drying in a vacuum oven, the gel was cleaned and filtered with distilled water to get rid of any remaining contaminants. After filtration, the wet powder was further dried in a vacuum oven for 1 hour at room temperature. The resulting dried solid was then ground into a fine powder and calcined for 2 hours at 300°C to obtain pure ZnO nanoparticles (Singh et al., 203).

This process involves the manufacture of zinc oxide (ZnO) nanoparticles using the sol-gel technique. Natural starches are used as chelating/stabilizing agents. To extract starch, potato peelings were gathered, cleaned, crushed, filtered, dried, and de-agglomerated. Using a sol-gel method, maize starch and potato peel starch were used as chelating agents in the ZnO synthesis. The ideal calcination temperature was found by using Thermogravimetric Analysis (TGA) on a xerogel that had been dried. TGA was carried out at temperatures between 25 and 1000°C in a nitrogen environment. After de-agglomeration, the powder was identified as Zc (corn starch) and Zp (potato peel starch). Unit cell properties were derived by applying Rietveld refinement. This work investigates the feasibility of using natural starches in the production of ZnO nanoparticles, providing information on their thermal and structural characteristics (De Almeida et a., 2023).

This method describes the formation of ZnO nanoparticles by sol gel method. $C_4H_{12}O_6Zn$, NaOH, was dissolved in a 12:1 M solution in a 500 ml ethylene glycol beaker. These combinations were constantly whirled for 30 minutes at 80 ∘C. Aqueous organic solvent was then added to the reaction mixture drop by drop until the pH reached 9.0. For three hours, the procedure was continuously shaken to produce a homogenous solution. Finally, the material was calcined at 500 °C for three hours to create a fine powder of zinc oxide nanoparticles (Sharma., et al 2023).

2.3 Synthesis by Microwave Assisted Method

Since microwave heating produces rapid, uniform heating and saves time and energy, it has become a practical synthesis technique for both organic and inorganic chemistry (Deepika et al., 2024). Furthermore, two conversion mechanisms—ionic conduction and dipolar rotation—are employed by microwave heating to convert electromagnetic radiation into thermal energy. This makes it possible to precisely heat the compounds in the reaction mixture according to how well they can absorb microwaves. Microwave-assisted synthesis has several advantages over conventional methods, including faster reaction rates, a greater range of feasible reaction conditions, higher yields, selectivity due to different microwave absorption qualities, careful reaction parameter control, and easier handling that allows for efficient parameter optimization (Shitu et al., 2024).

Using $Zn(NO_3)_2{\cdot}6H_2O$ as the precursor and CH_4N_2O as the fuel, which were dissolved in deionized water in a 1:5 M ratio and agitated for 30 minutes to achieve uniform blending, zinc oxide nanoparticles (ZnO NPs) were synthesized by the microwave-assisted chemical combustion technique. This mixture was exposed to microwave radiation for ten minutes, which caused it to heat up, get dehydrated, break down, and finally spontaneously burn into a powder that was frothy and solid. ZnO NPs were created as a result of the combustion process, which also released ammonia (NH_3), water vapor (H_2O), nitrogen gas (N_2), and carbon dioxide (CO_2). Calcinated ZnO NPs that were produced and then annealed for one hour at 500°C to improve crystallization. Furthermore, ZnO NPs were exposed to γ irradiation at three different dosages (25, 50, and 75 kg) with a Co-60 source; the resultant samples were labeled 25CZ, 50CZ, and 75CZ, respectively. This technique provides a quick and effective way to create ZnO nanoparticles, and it also has the benefit of γ irradiation for possible uses in radiation-induced changes (Khanam et al., 2024)

In this process ZnO nanoparticles was synthesized by employing the microwave irradiation technique, ZnO nanoparticles were created. In a beaker filled with 100 mL of deionized (DI) water, 0.5 mmol of zinc sulfate was added. The mixture was then continuously stirred at room temperature for 30 minutes while being exposed to 400 w of microwave radiation. After being heated to around 200 °C for ten to fifteen minutes, the resulting white precipitate (ZnO) was finally rinsed several times with water and ethanol. With different precursors, like zinc acetate and zinc nitrate, and the same reaction conditions, a similar process was used to get the same result (Mageswari et al., 2023).

In this method, deionized water (150 mL, 8.26 mol) was used to dissolve zinc acetate dihydrate (9.5 g, 0.04 mol), and NH_4OH was then added to reach pH 9. The combination was subjected to 20 cycles of 180 W microwave treatment (20 seconds on, 10 seconds off, or 6.40 min of radiation). The white precipitate underwent vacuum filtration, drying, and calcining (in air at 500°C for two hours at a rate of 5°C per minute). The powder that was produced is now known as ZnO/MW.

An analogous process was conducted when melamine (MEL) or grape pomace of Barbera extracts (E) were present. After dissolved in 50 mL and 200 mL of deionized water, respectively, extracts (E, 0.101 g) or melamine (Mel, 4 g) were added to raise the pH to 9. In parallel, dropwise additions of zinc acetate dihydrate (6.41 g, 0.029 mol) dissolved in 50 mL of deionized water were made to the extract solution. The combination was exposed to 180W of microwave radiation for 20 cycles, lasting 20 seconds on and 10 seconds off, for a total of 6.40 minutes of radiation. Following vacuum filtration, the white precipitate was dried (at 90°C for a whole night) and then calcined (in air, at 500°C for two hours, at a rate of 5°C per minute). ZnO/E/MW and ZnO/MEL/MW, respectively, are the labels applied to the material that follow (Gautier di Confiengo et al., 2024).

The aerial roots of F. benghalensis were initially collected in order to create the nanoparticles using this procedure. To get rid of any pollution, the item was carefully cleansed with tap water. Aerial roots that had been cleaned were allowed to air dry in the shade for three months. A grinder was used to pulverize the aerial roots, and 250 g of the powder together with ethanol were added to the soxhlet device. For seventy-two hours, the ethanolic extract was treated at between 80 and 90 degrees Celsius. The extract was concentrated at 40–50 oC at low pressure. ZnO NPs (zinc oxide nanoparticles) are made using two different ways in the production process. Plant extract is added to a zinc chloride solution in the first approach (A-ZnO NPs), and white ZnO NPs are precipitated by gradually adding sodium hydroxide after that. Drying, washing, and separation of the precipitate follow. To speed up the generation of nanoparticles, the same process is followed in the second technique (B-ZnO NPs), but after combining the plant extract with zinc chloride, the mixture is microwave-irradiated. Similar to the previous approach, the precipitate that results is handled in the same way (Dawar et al., 2024).

In this process, ZnO and $Zn_{0.5-x}Cr_xO$ nanoparticles (NPs) with x = 0.02, 0.04, and 0.06 M were produced using the microwave-assisted chemical combustion technique. Utilizing urea as the fuel and zinc nitrate hexahydrate and Cr (III) nitrate nonahydrate as precursors, pure and $Zn_{0.5-x}Cr_xO$ NPs were created. At room temperature, the reagents were dissolved in deionized water. Precursor solutions for zinc and Cr were combined in different molar ratios. To create a homogenous mixture, the precursor and fuel were combined immediately at a 1:5 molar ratio and agitated for 30 minutes. This clear solution was transferred to a beaker, where it was exposed to microwave radiation for ten minutes in a microwave oven to produce pure $Zn_{0.5-x}Cr_xO$ NPs (Khanam et al., 2024).

2.4 Synthesis by Co-Precipitation Method

The synthesis of ZnO nanoparticles has been proven using a number of techniques, including chemical bath deposition, co-precipitation, hot injection, hydro-and solvothermal, and microwave assisted method. The co-precipitation process was selected among these methods for the preparation of ZnO nanoparticles because of its high yield, low cost, and pure result (Patil et al., 2024).

Aloe Vera Gel (AVE) from Aloe barbadensis miller is extracted and combined with distilled water to create a pale-yellow solution after agitation and filtering. This process is the first step in the co-precipitation method's manufacture of zinc oxide nanoparticles (ZnO NPs). Precursor solutions are simultaneously made of sodium hydroxide, silver nitrate, copper nitrate trihydrate, and zinc nitrate hexahydrate. Next, the precursor solution is mixed at 80°C with AVE extract added in a 1:1 ratio until the pH reaches 10. The solution is then given time to settle, and centrifugation is used to gather the precipitate that forms. The precipitate is dried and milled into a fine powder after being repeatedly washed with distilled water and ethanol. It is then calcined at 250°C for four hours to produce the final ZnO (Rashid et al., 2024).

By using the chemical wet co-precipitation process, zinc oxide (ZnO) and ZnO nanoparticles doped with nickel may be synthesized in many stages. First, 1.125 g of KOH is dissolved in 10 ml of deionized (DI) water, then 2.202 g of zinc acetate dihydrate is dissolved in 100 ml of DI water. The precipitate is then formed by gradually adding the KOH solution dropwise while vigorously stirring the zinc acetate solution. After that, this precipitate is heated steadily to 70°C for three hours on a hot plate. Following the reaction, the white precipitate is centrifuged and cleaned with DI water before being dried for 24 hours at 80°C. After that, the powder is further annealed for four hours at 600°C in a furnace. This procedure is carried out several times to ensure uniformity in the synthesis, producing outcomes that are comparable each time. Zinc acetate and KOH solutions are carefully mixed during the synthesis process to provide pure ZnO and nickel-doped ZnO nanoparticles, which are then precipitated, cleaned, dried, and annealed (Ahmad et al., 2024).

Chemical ZnO NPs were synthesized using the co-precipitation approach. First, 400 grams of Nigella sativa seed were ground into a fine powder and dissolved in 600 milliliters of ethanol for a 24-hour period at 100 degrees Celsius. After a full day, take the solution off the hot plate, let it cool, and then strain it through filter paper. The seeds of Nigella sativa were extracted into a dark green liquid. Utilizing the green synthesis technique, zinc oxide nanoparticles were produced (Fakhar-e-Alam et al., 2024).

There are many stages involved in creating zinc oxide nanoparticles (ZnO NPs) doped with Plectranthus chaudocanum (PLE) extract. The first step involves gathering P. chaudocanum L. leaves from Vietnam, cleaning, drying them in the air, and powdering them into a fine form. Ten grams of the powdered leaves are extracted using ultrasonic in a 1:1 ethanol and distilled water combination at 60°C for an hour. This technique adheres to a previously defined protocol. To extract P. chaudocanum extract, which is then kept at 4°C for later use, the extract is cooled and then centrifuged and filtered. For the manufacture of ZnO NPs in further investigations, this extract is used as a dopant (Truong., 2023).

Zinc oxide (ZnO) and its doped variations were synthesized using the chemical co-precipitation process. Initially, distilled water was used to dissolve the proper concentrations of ZnCl2, LaCl3, $CeCl_3{\cdot}7H_2O$, and 0.1 M EDTA. By titrating the solutions with 4 M NaOH while continuously stirring, the pH of the mixtures was brought to 12. The solutions were then heated to 60°C for two hours while being stirred continuously. After that, they were cleaned with distilled water until the pH reached 7. The resultant white precipitates were crushed, dried for eighteen hours at 100°C, and then calcined for four hours at 550°C (Al Bitar et al., 2023)

2.5 Green Synthesis of ZnO Nanoparticles

Zinc oxide nanoparticles (ZnO NPs) can be produced using a variety of techniques, such as physical, chemical, and biological ones. Even while physical and chemical approaches are efficient, they can be expensive and pose a risk to the environment since they involve the use of hazardous materials. On the other hand, because to their low cost and environmental friendliness, biological techniques—in particular, green synthesis utilizing plant extracts—have drawn interest. These techniques avoid the need of extra chemical agents by using naturally occurring plant components, such as flavonoids, glycosides, polyphenols, terpenoids, and enzymes. This makes the process both economical and ecologically friendly (Ismail et al., 2023).

Using green synthesis techniques, zinc oxide (ZnO) nanoparticles are produced. Algae or their extracts serve as effective reducing and capping agents. Algal bioactive substances, such as phytochemicals and biomolecules, are essential for the reduction of metal ions and the subsequent production of nanoparticles. Metal-induced stress triggers intracellular production in algal cells, which releases bioactive compounds that bind metal ions and start the formation of nanoparticles. A sequence of bio reduction stages, including activation, growth, nucleation, and termination phases, are made possible by functional groups found in the algal extract. These steps aid in the reduction of metal ions and the creation of crystalline ZnO nanoparticles. The synthesis parameters, including temperature, pH, and reaction time, may be manipulated by researchers to customize the size, shape, and characteristics of ZnO nanoparticles for a range of uses (Ismail et al., 2023)

First, the gathered Pisonia alba leaves were thoroughly cleaned to eliminate any dust or debris, and then they were ground into a fine powder to start the creation of zinc oxide nanoparticles, or ZnO NPs. After that, 50 mL of water and 10 g of the dried leaf powder were cooked at reflux conditions for two hours at 100°C. The mixture was then filtered using Whatman No. 1 filter paper to produce an aqueous leaf extract. The aqueous extract was cooled to 4°C before being used to produce ZnO NP. Concurrently, 0.1 M zinc acetate dihydrate was produced and mixed with 50 mL of deionized water at room temperature for 15 minutes before adding it to the leaf extract. Using a magnetic stirrer, the resultant mixture was aggressively agitated for two hours at 70°C. After completion of the reaction, the precipitate was allowed to settle before being centrifuged for 15 minutes at 6000 rpm in order to separate it from the reaction solution. Any leftover contaminants were washed away with deionized water in subsequent washings, and the precipitate was then dried at 80°C in an air oven. After synthesis, the sample was calcined in a muffle furnace for two hours at 500°C. At last, the ZnO NPs underwent powdering, drying, and storage within an airtight receptacle (MuthuKathija et al., 2023).

A green technique was used to create zinc oxide nanoparticles, or ZnO NPs. A beaker was first filled with 100 mL of 0.1 M ZnSO4.7H2O solution. Next, drop by drop, 20 mL of room-temperature neem extract was added. After adding 2M NaOH solution to bring the pH of the mixture down to 12, it was agitated for 4 hours at 60°C, producing a paste that had a deep yellow color. After filtering the mixture, the filtrate's color changed from pale yellow to pale white, indicating that zinc salt had been reduced to ZnO NPs. This observation was supported by UV-Vis spectra. The filtrate was then dried in an oven at 80°C for 12 hours, resulting in a paste that was then further annealed in a ceramic crucible at 500°C for 3 hours, producing a light white powder. This technique offers a productive and environmentally friendly way to create ZnO NPs, which may find use in a variety of industries (Yadeta Gemachu, 2024).

Green synthesis was used to create zinc oxide nanoparticles (ZnO NPs). Fresh fruits were cleaned, allowed to dry, crushed, and sieved to create a fine powder before being used to make an aqueous extract of N. latifolia fruit. 20 grams of this powder were boiled for 30 minutes at 60°C in 400 milliliters of deionized water. The resulting fruit extract was filtered and utilized right away. 5 g of zinc nitrate hexahydrate was added to 50 mL of this extract, which was heated in a beaker at 60–80°C on a magnetic stirrer, and stirred until yellow precipitates appeared in order to synthesize nanoparticles. After being cleaned with distilled water and ethanol and dried in an oven at 60°C for four days, the final product was calcined for two hours at 400°C. Finally, the resulting white powder was preserved for examination in an airtight container. This process provides a productive and environmentally friendly way to produce ZnO NPs, which may find use in a variety of sectors (Abegunde et al., 2024).

2.6 Synthesis of ZnO by Laser Ablation Technique

One of the simplest and most adaptable techniques for creating various kinds of nanostructured materials is Pulsed Laser Ablation in Liquids (PLAL). PLAL is superior than traditional methods in many ways (Kadhum, 2024). Using high-purity ZnO targets and in-liquid, room-temperature pulsed laser ablation (PLAL) technology, colloidal solutions of metal nanoparticles were created for the investigation. There were other steps in the procedure, such as using ethanol to clean and polish the metal target and ultrasonic water filtration to get rid of contaminants. Following cleaning, the target was submerged in distilled water in a glass vial with a precise volume (5 ml) and liquid height (4 mm) above the target's surface. Three distinct pulses of 400, 500, and 600 millijoules each were used to blast the surface of the metal target. The procedure produced colorful colloidal solutions with nano-metallic particles, which changed the water's color visibly after it was eradicated (Kadhum, 2024).

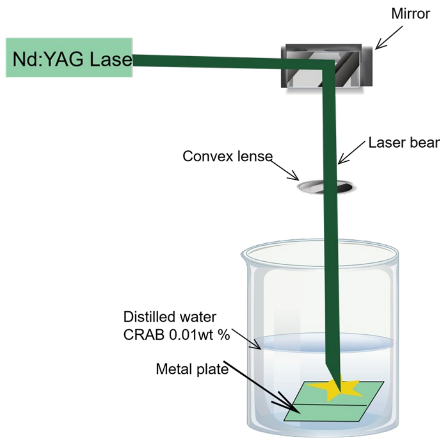

Figure 3: Pulsed Laser Ablation in Liquids (PLAL).

For the purpose of creating zinc oxide (ZnO) nanoparticles (NPs) by pulsed laser ablation (PLA), a 99.9% pure zinc target was ablated for 30 minutes in 80 milliliters of purified water. An average particle concentration of around 0.3 m/L was obtained by measuring the target mass loss before and after ablation. The colloidal solution was then dried in air at around 60°C, and the powder that was left over was calcined in a muffle for four hours at 400°C. First, separate colloidal solutions from the ablation of silver (Ag) and zinc (Zn) targets were collected in order to construct a composite material. After that, these solutions were combined at a mass ratio of 1:199 for Ag:ZnO. The resultant colloids were treated for 15 minutes in an ultrasonic bath, then they were dried in 60°C air and calcined at 400°C. The NP samples that were obtained were named ZnO and ZnO-1Ag.

To create zinc oxide (ZnO) nanoparticles (NPs), high-purity Zn powder (99.8%) was pressed into a 2 x 2 x 0.2 cm zinc metal target. Subsequently, this target was positioned at the base of a rotating beaker with 3 milliliters of deionized water. For ablation, a concentrated laser beam was employed. The thickness of the aqueous layer above the Zn pellet was consistently maintained at 0.7 cm in order to ensure experimental reproducibility. To achieve enough laser fluence, the plano-convex lens with a 110-mm focal length was used to estimate the laser beam spot size to be 1.5 mm on the Zn pellet. For 300 laser pulses each, the laser intensity was adjusted to 400, 600, and 800 mJ/pulse, producing nanoparticles (Hadi et al., 2023).

An Au plate was soaked in 3 mL of deionized water (DW) in a glass vial for the experiment, and it was then ablationed. During the laser ablation (LA) procedure, a total of 200 pulses with a laser intensity of 800 mJ were used, and the target did not move. After that, 3 mL more of DW was put to a glass beaker with a Zn pellet at the bottom, and it was individually irradiated under the same settings as the Au ablation. The resultant Au nanoparticle (NP) solution turned from light pink to deep pink as the laser intensity rose, whereas the ZnO NP solution went from pale gray to pale yellow. Au NPs to ZnO NPs were mixed in various volumetric ratios (1:3, 1:1, and 3:1 v/v) to create Au/ZnO nanocomposites (NCs). Following the mixing of the two colloidal solutions, 800 mJ for 100 pulses of second harmonic laser pulses were focused on the solution's surface using a 532 nm laser (Alhujaily et al., 2023).

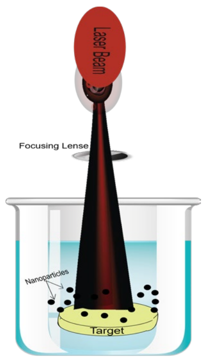

Figure 4: laser ablation (LA) procedure

3. Applications of ZnO Nanoparticles

Nanoparticles of zinc oxide (ZnO) are popular in environmental remediation due to their strong reactivity, adsorption capacity, and photo degradability (Altammar, 2023). This is because they have these traits. ZnO nanoparticles can cure environmental pollutants in several ways. These mechanisms include organic pollutant degradation, heavy metal removal, and antibacterial action (Chakraborty and Pandey 2023). The goal of this thorough study is to investigate ZnO nanoparticles in environmental cleanup. The efficacy and procedures of ZnO nanoparticles are explained in detail. The overview was created using a wide range of studies and publications.

3.1 Photocatalytic Degradation of Organic Pollutants

ZnO nanoparticles are efficient photo catalysts that destroy several organic contaminants when exposed to UV light (Kadhim et al., 2023). ZnO generates electron-hole pairs when exposed to UV light. The phenomenon's mechanism hinges on this. Electron-hole couples create reactive oxygen species (ROS), including hydroxyl radicals. These reactive oxygen species (ROS) oxidize organic molecules, breaking down complicated contaminants into safer chemicals (El Golli et al. 2023). Two researchers in 2009 showed that zinc oxide (ZnO) photo catalyzed methylene blue degradation under UV light (Motelica et al., 2023). The research showed considerable degradation efficiency. Instead to bulk ZnO, ZnO nanoparticles have a high surface area to volume ratio, which increases the number of reactive sites and photocatalytic activity. This is because nanoparticles have more surface area than bulk ZnO. Saravanan et al. in 2013 also investigated adding metals like silver to ZnO to increase its capacity to absorb visible light and degrade photo catalytically (AlSalhi et al., 2023).

3.2 Heavy Metal Removal

Additionally, ZnO nanoparticles have shown promising results in heavy metal adsorption and removal from polluted water (Akpomie et al., 2023). They also showed promise here. Nanoparticles have many active sites for heavy metal ion adsorption due to their enormous surface area. Because nanoparticles are tiny. Studies have examined whether ZnO nanoparticles can remove lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) from aqueous solutions (Kumari, 2023). Sharma and colleagues (2010) examined ZnO nanoparticle lead(II) ion adsorption. Their investigation showed that pH affects adsorption, with pH 5 being ideal. The study found that ion exchange controlled adsorption. This technique used ZnO surface hydroxyl groups (Kumar et al., 2024; Shnawa et al., 2024)

3.3 Antimicrobial Activities

ZnO nanoparticles' antimicrobial characteristics aid water disinfection. It has been shown that ZnO nanoparticles can kill bacteria, fungus, and algae. Antibacterial action comes from reactive oxygen species (ROS), which may damage microorganism membranes, proteins, and DNA. ZnO nanoparticles might kill Staphylococcus aureus and E. coli (Jones et al., 2008). Particles damaged membranes, killing cells. This property may help avoid biofilms in water treatment systems, improving water purification (Osajima et al., 2023).

3.4 UV Protection

Zinc oxide nanoparticles absorb UV light, making them popular in sunscreens and other personal care products. This is because nanoparticles are employed in many products (Subramani and, 2024). UV A and UV B light is scattered and absorbed by nanoparticles, protecting the skin. This is done without leaving the white residue generated by regular zinc oxide compositions. ZnO nanoparticles provide long-lasting protection since they do not deteriorate in the sun like other organic UV filters. This has major benefits (Lawrynowicz et al., 2024).

3.5 Electronics and Photonics

ZnO nanoparticles are widely used in electronics due to their semiconductor characteristics, rapid electron mobility, and broad bandgap. Differentiators, sensors, and transparent conductive coatings can be made with their help (Alqarni et al., 2024). Photonics uses zinc oxide nanoparticles for light-emitting and laser diodes. Because ZnO nanoparticles release light when triggered. This capacity is enhanced by the nanoscale particle size, which allows quantum confinement processes (Sangeetha et al., 2024).

3.6 Catalysis

ZnO nanoparticles are versatile catalytic agents used in many chemical processes. They were used in biodiesel production and organic chemical synthesis. Nanoparticles' enormous surface area helps them interact with reactants, increasing their catalytic activity. ZnO nanoparticles stimulate esterification and transesterification to make biodiesel from vegetable oils and animal fats. Biodiesel is made from these two fats; therefore, this is crucial.

3.7 Gas Sensing

Gas sensing applications may benefit from ZnO nanoparticles' capacity to absorb gases and affect their electrical resistance. Their sensitivity to VOCs, carbon monoxide, and hydrogen is also relevant. This is because ZnO nanoparticles are attractive candidates for safety monitoring systems, air quality sensors, and industrial and automobile emission controls (Eriksson et al., 2009).

3.8 Antifouling and Anticorrosion

ZnO nanoparticles can provide antifouling and anticorrosion, chemical coatings can attain their full potential. Marine paints using nanoparticles can prevent barnacles and algae from growing on ship hulls. This effect is possible. This increases gasoline economy and reduces car maintenance costs. ZnO nanoparticle coatings resist metal corrosion, making them useful in severe or humid conditions. These coatings also prevent rusting (Zhan et al., 2024)

3.9 Biomedical Applications

ZnO nanoparticles have biomedical uses due to their antibacterial, antifungal, and anticancer characteristics. Dental composites and wound dressings include them to prevent infections and decay, respectively (Youssef et al., 2024). Additional research has examined their potential as drug delivery vehicles, notably in targeted cancer therapy. Because they create reactive oxygen species, they can selectively kill cancer cells (Thannasi and Sadaiyandi., 2023).

3.10 Energy Storage and Generation

Energy companies use ZnO nanoparticles to make batteries and supercapacitors. This is because ZnO nanoparticles allow fast electron transport. They also form dye-sensitized solar cell photoanodes. They increase conversion efficiency by providing a broad surface area for dye absorption and electron passage into the cell. The goal is to boost conversion efficiency (Sardar et al., 2023).

3.11 Food Packaging

Food packaging materials are being modified to add zinc oxide nanoparticles to improve safety and shelf life. Antibacterial and UV-blocking qualities of these compounds help prevent infections and protect products from sunshine. Both qualities make these drugs work properly. ZnO nanoparticles may be used in many practical applications, demonstrating its versatility and promise in many technological and industrial fields. The fact that any application may take use of ZnO's unique chemical and physical properties at the nanoscale shows how important material science is in creating new solutions and advancing present technology (Kumar et al., 2024). Zinc oxide (ZnO) nanoparticles have several environmental remediation uses. These nanoparticle-based applications leverage photocatalytic, adsorptive, and antibacterial capabilities to solve environmental issues (Rani and Shanker., 2023). The following are specialized uses of ZnO nanoparticles, particularly in environmental remediation:

3.12 Water Treatment

ZnO nanoparticles are commonly used in water treatment. They also remove various contaminants from water, including viruses, toxic heavy metals, organic and inorganic pollutants, and others. This makes them precious. ZnO nanoparticles can cure dye- and heavy-metal-containing industrial effluent. These nanoparticles often save money and enhance efficiency over traditional treatments (Osajima et al., 2023).

3.13 Air Purification

Photocatalytic ZnO nanoparticles can break down airborne VOCs and other hazardous pollutants. When exposed to UV radiation, ZnO nanoparticles release reactive oxygen species. Reactive oxygen species convert poisons into water and carbon dioxide. This application helps regulate indoor air quality, which must be low in volatile organic compounds for human health (Rezeki and Zainul., 2024).

3.14 Soil Remediation

ZnO nanoparticles can clean up pesticide-, heavy metal-, and other-contaminated soils. This can be done by eliminating soil pollutants.

Chemical processes stabilize or change pollutants into less hazardous forms (Haghsheno and Arabani, 2023). Zinc oxide nanoparticles can transform harmful chromium (VI) into less hazardous (III) in contaminated soils, lowering environmental risk (Jadoun et al., 2024).

3.15 Antibacterial Treatment for Environmental Surfaces

ZnO nanoparticles' antibacterial properties can be used to treat surfaces in germ-prone locations like hospitals (Shukla, 2022). This is possible. ZnO nanoparticle coatings may prevent disease and maintain cleanliness by limiting bacteria and other microbes (Sonawane et al., 2023).

3.16 Photocatalytic Degradation of Pesticides

Sometimes ZnO nanoparticles decompose pesticides on agricultural items and runoff water. To produce the intended impact (Ragavendran et al., 2023). These molecules break down complex pesticide compounds due to their photocatalytic activity in UV light. This keeps these toxins out of the food chain and waterways, where they may harm humans and the environment (El Golli et al., 2023).

3.17 Oil Spill Cleanup

ZnO nanoparticles' hydrophobic properties allow them to absorb, harden, and extract crude oil from water. This is possible using nanoparticles. This program is useful for coping with oil spills, which can have serious environmental consequences (Selim et al., 2024). ZnO nanoparticles may aggregate oil, making cleanup easier. This would make oil collection and removal from the water surface easier (Bhandari et al., 2023).

3.18 Enhancing Bioremediation

ZnO nanoparticles can increase bioremediation by fostering microorganisms that break down contaminants. This environment may be caused by ZnO nanoparticles (Ahmad et al., 2023). The creation of a better environment makes this environment possible. Nanoparticles may speed microorganisms' organic contamination removal. This will allow faster cleanup (Modi et al., 2023).

3.19 Sediment Remediation

Zinc oxide nanoparticles can break down and immobilize organic and inorganic contaminants in sediments. This is because nanoparticles accelerate pollutant degradation. This use is essential for restoring aquatic habitats harmed by industrial discharges and urban runoff (Stetten et al., 2023).

3.20 Antifungal Applications

ZnO nanoparticles are antibacterial and antifungal (Terea et al., 2023). In wet environments, these antifungal properties may be crucial for mold and mildew management. This application helps maintain structural integrity and air quality in buildings and other structures (Momeni et al., 2024). The examples below show that ZnO nanoparticles can perform several environmental cleanup activities. As shown by their success in many contexts, they have the potential to be one of the most sustainable and flexible solutions to some of the most serious environmental issues (Jadoun et al., 2024).

4. Conclusion

Zinc oxide (ZnO) nanoparticles have become a strong environmental cleanup tool in recent years. These nanoparticles have several uses, many of which aim to address environmental challenges. These materials' photocatalytic, adsorptive, and antibacterial properties allow for effective interventions in many fields. These features allow for oil spill control, air, water, soil, and sediment cleanup. Another example of ZnO nanoparticles' adaptability is its ability to remove heavy metals, break down organic contaminants, and reduce microbiological dangers. ZnO nanoparticles' applications in ultraviolet (UV) protection, electronics, energy storage, and food packaging demonstrate their potential to advance technology and the environment.

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