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ADVANCEMENTS IN ZNO NANOSTRUCTURES: PIONEERING ENVIRONMENTAL AND AGRICULTURAL REMEDIATION STRATEGIES

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ABSTRACT
Globally, initiatives to clean up the environment and agriculture are increasing as worries about pollution, climate change, and food security grow. Novel approaches are being explored, such as the removal and degradation of pollutants using cutting-edge materials like zinc oxide (ZnO) nanostructures. These solutions put sustainability first, seeking to improve soil health and agricultural fertiliser management while reducing environmental harm. Farming techniques are undergoing a transformation as a result of nanotechnology, which is lowering environmental hazards, increasing efficiency, and creating nano fertilisers and sensors. This change is a result of a growing understanding of how environmental and agricultural issues are interwoven, which is motivating the use of holistic approaches to guarantee sustainability and resilience in the face of changing threats. This study focuses on zinc oxide (ZnO) nanostructures as prospective instruments for combating environmental pollution and improving agricultural sustainability. ZnO nanostructures have strong photocatalytic activity, destroying different organic contaminants under sun radiation. In agriculture, nano fertilizers increase soil quality, plant development, and crop output. Furthermore, ZnO nanoparticles enable precision agriculture through nano sensor applications. The study critically assesses current advances in ZnO nanostructure production, characterisation, and application, addressing important difficulties and emphasising their promise for long-term solutions to pollution reduction and agricultural development.

KEYWORDS: *ZnO Nanostructures, Environmental remediation, Agricultural remediation, Pollution mitigation, Nanotechnology Sustainability.*

1. Introduction to Environmental remediation

The 21st century has brought significant environmental difficulties, which include pollution of the air, water, and soil to natural resource depletion and biodiversity loss. In response to these serious concerns, the scientific community has increasingly turned to nanotechnology as a possible method of environmental rehabilitation.[1, 2] Nanomaterials, defined by their distinct physical, chemical, and biological characteristics at the nanoscale, provide fresh options for combating environmental degradation and restoring ecological balance.[3, 4]

The use of nanostructures in environmental remediation signifies a paradigm change in how we handle resource management and pollution reduction. While traditional remediation methods can include expensive treatment plans, long treatment durations, and low efficacy, nanotechnology offers prospects for more effective, economical, and long-lasting solutions. Through the utilization of nanostructures' exceptional characteristics, including their elevated reactivity, adjustable surface chemistry, and high surface area-to-volume ratio, scientists are introducing novel strategies to tackle an extensive array of environmental pollutants. Nanoparticle-based remediation is at the forefront of environmental nanostructures.[5, 6] Nanoparticles, which are particles with size on the nanometre scale, have special features that make them extremely effective at pollution removal and destruction. Engineered nanoparticles, such as metal oxides (e.g., titanium dioxide, zinc oxide), carbon-based nanomaterials (e.g., graphene, carbon nanotubes), and quantum dots, have exceptional catalytic, adsorptive, and photocatalytic properties, allowing for the efficient removal of contaminants like heavy metals, organic pollutants, and pathogens from air, water, and soil.[7, 8]

Nanostructure-based environmental remediation is a dynamic and quickly developing topic that has the potential to completely change how we deal with pollution in the environment and protect the world for coming generations. Researchers are in a position to create ground-breaking solutions that reduce pollution, rebuild ecosystems, and advance sustainable development by utilizing the special qualities of nanostructures and welcoming multidisciplinary cooperation. Transition metal oxide nanomaterials, especially zinc oxide (ZnO), have attracted a lot of interest lately due to their regulated microstructure and morphology, which open up a world of better qualities that may be used in many different applications.[9 – 11] As a direct wide band-gap semiconductor, ZnO is unique in that it has a low crystal growth process, a high exciting binding energy, and is reasonably priced. Its physicochemical characteristics, including as its high transparency, UV excitation, anti-radiation stability, and room-temperature piezoelectricity, make it a flexible option for a range of uses. Utilizing ZnO's photoelectric, photochemical, and redox capabilities has become a viable option for resource and environmental applications in response to growing energy crises and environmental concerns.[12, 13] Widespread application in energy storage, electronics, optics, and photocatalysis is made possible by the broad variety of ZnO nanostructures and combinations, which provide multi-dimensional morphologies with previously unheard-of diversity and control. ZnO's photocatalytic ability for environmental clean-up is gaining attention, which is noteworthy. Presumably, a paradigm shift toward sustainable solutions is reflected in the notable increase in annual publications including the use of photocatalysis. Zinc oxide (ZnO) is essential for solving modern problems, as demonstrated by the shift to photocatalytic uses in environmental situations.[14 – 16]

However, typical free-standing forms of ZnO, such as powders or nanoparticles, have inherent limitations, including agglomeration and secondary contamination concern. To overcome these limitations, researchers have used immobilized versions of ZnO and attached them to recyclable substrates for increased efficiency and environmental friendliness. This sector focuses on the controlled development of immobilized ZnO nanostructures using readily recyclable substrates such as glass plates, metal foils, silicon wafers, and flexible polymer sheets. This review summarizes our contributions and a few scholarly papers that outline the state-of-the-art for immobilized ZnO nanostructures and their environmental applications. Interestingly, the study only includes materials that are backed by recyclable substrates, so it is both realistic and sustainable. The synthesis process's substrate-independence is further highlighted by the use of seed layers, which improves scalability and repeatability.[17 – 20]

1.1. Over view of Environmental pollution

Environmental pollution is a complex and widespread issue that endangers ecosystems, human health, and the planet's general well-being. It refers to the pollution of air, water, soil, and living beings by numerous pollutants caused by human activities, industrial operations, agricultural practices, and natural events. From heavily crowded metropolitan centres to distant wilderness regions, no corner of the Earth is immune to the effects of pollution, emphasizing the critical need for coordinated global action to address this grave crisis.[21 – 23]

1.1.1. Air Pollution

Air pollution is defined as the presence of dangerous pollutants in the Earth's atmosphere, including particulate matter, nitrogen oxides, sulfur dioxide, volatile organic compounds, and heavy metals. It comes from car emissions, industrial activity, agricultural burning, and fossil fuel combustion for electricity generation.[24, 25] Air pollution can harm respiratory health, cardiovascular function, and general well-being, causing respiratory disorders, heart attacks, strokes, and early death. Furthermore, air pollution contributes significantly to climate change by worsening global warming through the emission of greenhouse gases and aerosols.[26, 27]

1.1.2. Water Pollution

Water pollution occurs when pollutants such as industrial chemicals, agricultural runoff, sewage, and plastic trash degrade the quality of freshwater bodies including rivers, lakes, and groundwater reservoirs. Water contamination is caused mostly by discharges from industrial sites, inappropriate waste disposal methods, and urban runoff. Contaminated water is hazardous to human health, causing waterborne illnesses such as cholera, typhoid fever, and dysentery. Furthermore, aquatic ecosystems incur negative consequences such as habitat degradation, biodiversity loss, and food chain disruptions, which contribute to ecological imbalances and fish stock decreases.[28, 29]

1.1.3. Soil Pollution

When dangerous materials, such as pesticides, heavy metals, and industrial chemicals, build up in the soil, it becomes unfit for farming, plant development, and ecosystem function. This condition is referred to as soil pollution, often called land contamination. Industrial production, mining, inappropriate waste disposal, and chemical fertilizer and pesticide usage in agriculture are some of the activities that lead to soil contamination. Through direct contact, eating contaminated food, and the transmission of pollutants to groundwater sources, polluted soils provide health concerns to humans. Moreover, the deterioration, erosion, and loss of arable land caused by soil contamination endanger ecosystem resilience and food security.[30 – 32]

1.1.4. Noise Pollution

Noise pollution is the term used to describe excessive or undesired noises that disturb the natural environment and lead to stress, irritation, and hearing loss in both people and wildlife. Transportation-related noise pollution comes from railroads, airplanes, and cars as well as from factories, building sites, and leisure-related noise pollution such concerts and athletic events. Long-term excessive noise exposure can have negative health impacts, such as elevated blood pressure, insomnia, memory loss, and communication difficulties. Noise pollution also compromises biodiversity and the stability of ecosystems by upsetting wildlife habitats, changing animal behaviour, and interfering with mating calls and navigation.[33 – 35]

1.1.5. Nutrient Pollution

Nutrient pollution in agriculture stems from excessive use of chemical fertilizers and improper management of livestock manure. Chemical fertilizers can runoff into water bodies, causing nutrient imbalances and promoting algal growth. Similarly, inadequately handled livestock waste releases nutrients, pathogens, and antibiotic residues into the environment, contaminating water sources and exacerbating algal blooms. Effective nutrient management and proper waste disposal are crucial for mitigating this pollution and safeguarding water quality.

1.1.6. Light Pollution

Light pollution, also known as photo pollution, arises when artificial light sources generate excessive or misdirected light, interfering with natural darkness, obscuring celestial visibility, and disrupting circadian cycles in humans and animals. Light pollution is commonly caused by urban streetlights, business signs, outdoor advertising, and industrial operations.[36, 37] The widespread glare of artificial light at night not only obscures the stars and celestial bodies, but it also interrupts nocturnal wildlife behaviour, distorts migratory patterns, and alters ecosystems' natural cycles.

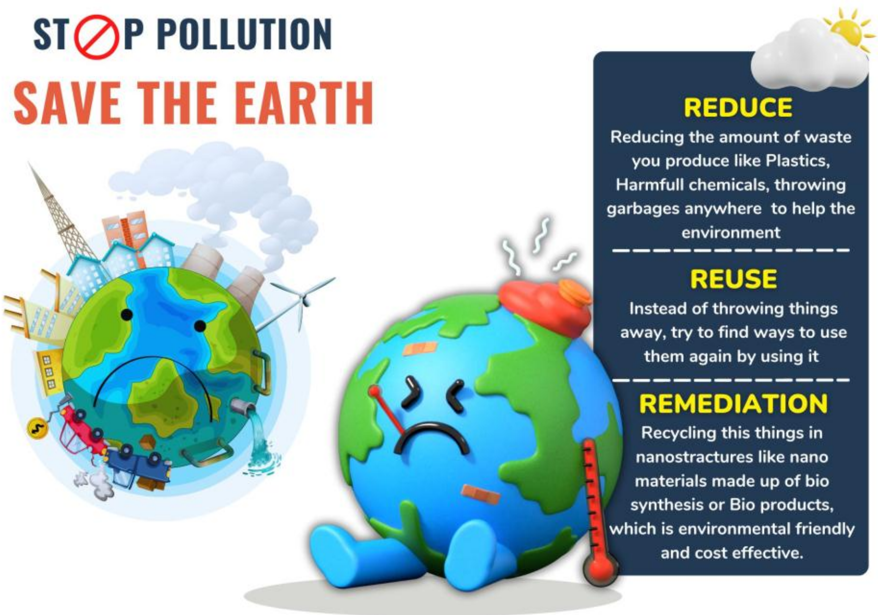

Figure 1: Environmental Pollution "Stop Pollution, Save the Earth".

Furthermore, light pollution has a negative impact on human health, leading to sleep problems, disrupting melatonin synthesis, and increasing the risk of obesity, diabetes, and several malignancies.[38, 39]

Global health, biodiversity, and sustainable development are generally seriously threatened by environmental degradation, which makes it imperative to take immediate action to lessen its effects and encourage environmental stewardship. Environmental contamination is depicted in Fig. (1) along with methods for its remediation, reuse, and reduction. Multidisciplinary strategies, cutting-edge technology, and cooperative alliances between businesses, governments, civil society groups, and private citizens are all necessary to combat pollution. We can preserve the Earth's ecosystems, safeguard human health, and ensure a more resilient and sustainable future for future generations by putting pollution prevention measures into place, adopting cleaner production methods, supporting renewable energy sources, and embracing sustainable lifestyles.[40 – 43]

2. Nanotechnology Application for environmental and agricultural remediation

The term "Nanotechnology in Environmental Remediation" describes the use of materials and procedures at the nanoscale to the problem of environmental contamination and pollution. Because of their special qualities, nanomaterials—such as nanoparticles and nanocomposites—are very useful in eliminating contaminants from soil, water, and the air. Through the utilization of nanomaterials' large surface area, reactivity, and catalytic properties, scientists may create novel approaches to address remediation problems such as organic pollutant degradation, heavy metal removal, and polluted environment purification. Nanotechnology presents viable paths for effective and sustainable environmental restoration, with the ability to reduce pollution, save ecosystems, and improve human health.[44 – 46]

"Nanotechnology in Environmental Remediation" is a modern strategy for dealing with the ubiquitous and intricate problems of environmental contamination and pollution. In order to take advantage of special qualities and phenomena that appear at this size, nanotechnology entails manipulating matter at the nanoscale, which is normally measured in nanometres, ranging from 1 to 100. Nanotechnology presents previously unheard-of chances to create effective, affordable, and long-lasting solutions for reducing pollution, repairing ecosystems, and preserving human health in the context of environmental restoration.[47 – 49] Due to their impressively high surface area-to-volume ratio, which allows for improved reactivity and adsorption capabilities over bulk materials, nanoparticles are advantageous in environmental clean-up. A broad range of contaminants may be effectively removed from air, water, and soil by using nanoparticles, which include metal oxides (such as titanium dioxide, iron oxide), carbon-based nanomaterials (such as graphene, carbon nanotubes), and nanocomposites. These nanoparticles have special physicochemical features.[50 – 52] The removal of organic contaminants, heavy metals, and recently found poisons from groundwater and wastewater sources are just a few of the water remediation issues that nanotechnology may help with. Nanoparticles may be engineered to selectively adsorb or catalyse the breakdown of contaminants, making their removal from aquatic environments simpler. Moreover, nanomaterial-based membranes and filters offer efficient methods of purifying water by trapping impurities selectively and allowing only pure water molecules to flow through.[53, 54] Nanotechnology is essential to the development of sophisticated materials and systems used in air remediation to capture particulate matter, volatile organic compounds (VOCs), and other air contaminants. Through catalytic oxidation or reduction processes, catalysts based on nanoparticles can aid in the decomposition of hazardous gasses and produce less toxic by-products. Additionally, the use of nanoparticles into air filtration systems can improve the effectiveness of pollution absorption and extend the life of filters. Furthermore, by enabling the targeted delivery of remediation agents to polluted locations and aiding the breakdown or immobilization of contaminants in soil matrix, nanotechnology offers potential for soil remediation. By interacting with soil pollutants, functionalized nanoparticles with certain surface coatings or ligands might facilitate their sequestration or change into less hazardous forms. Furthermore, the utilization of nanomaterials can be combined with soil amendments or bioremediation methods to improve remediation effectiveness and quicken the process of pollutant breakdown.[55 – 57]

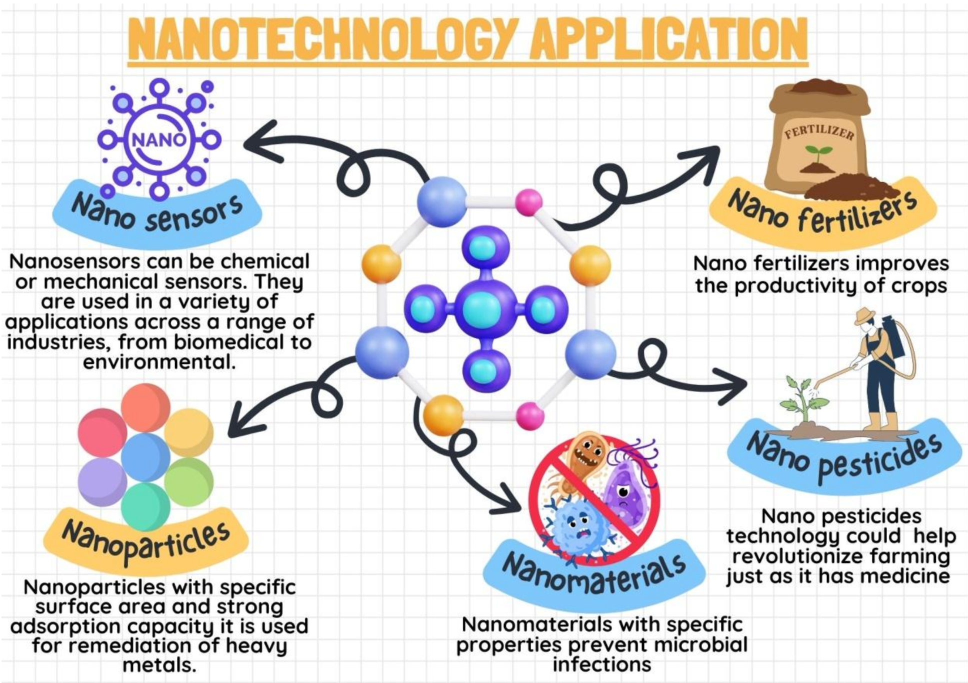

Figure 2: Different applications of Nanotechnology.

However, there are obstacles and factors to take into account with regard to environmental health and safety, as well as the long-term effects of nanomaterials on ecosystems and human health, coupled with the enormous potential of nanotechnology in environmental rehabilitation. Fig. (2), defines different applications of nanotechnology for the remediation of environment to make it clean and less harmful. Ensuring the safe and sustainable deployment of nanotechnology for environmental remediation requires the implementation of regulatory frameworks, responsible nanomaterial design and production methods, and comprehensive risk assessments. By utilizing the special qualities of nanoparticles, nanotechnology provides a revolutionary method of environmental rehabilitation, generating creative solutions to problems with contamination and pollution.[58-59] Researchers and practitioners may contribute to the creation of more sustainable, healthy, and clean ecosystems for current and future generations by utilizing the potential of nanotechnology.[60-64] Nanotechnology has emerged as a potent tool for agricultural remediation, providing novel solutions to environmental issues while supporting sustainable farming practices. Nanomaterials, including nanofertilizers, nano sensors, and nano pesticides, serve critical roles in improving soil health, optimising nutrient management, and reducing pollution. Nano fertilizers use controlled release methods to provide accurate nutrient delivery, improve plant development, and reduce environmental impact. Nano sensors give real-time data on soil and crop health, allowing for more informed decisions about irrigation, fertilisation, and pest control. Nano pesticides provide effective pest control with less environmental harm than traditional chemical pesticides. Furthermore, nanomaterials such as zero-valent iron nanoparticles hold potential for soil remediation by effectively immobilising pollutants and restoring soil fertility.[65-68]

3. Biomedical Applications of Zinc Oxide Nanoparticles (ZnO NPs)

3.1. Cancer Treatment and Diagnosis

Conventional cancer treatments often face limitations like low bioavailability and severe side effects. Modern therapies, including the use of nanoparticles, offer promising solutions.[69] Zinc oxide nanoparticles (ZnO NPs) are particularly noteworthy for their ability to generate reactive oxygen species (ROS), improve permeability, and retain in tumor sites, making them effective in cancer treatment.[70-71]

- **Key Study:** Singh et al. developed hybrid nano systems combining chymotrypsin protein with AzureC (AzC) and ZnO NPs.[72] These nanoconjugates showed significant cytotoxic effects against A-549 adenocarcinoma cells and potential for phototherapies.[73]
- **Dose and Size Sensitivity:** Research by Sarkar et al. emphasized that cytotoxicity depends on nanoparticle dose, exposure duration, cell type, and size.[74-76]

3.2. Wound Healing

Burn wound treatment remains challenging, especially with multidrug-resistant infections.[77] ZnO and silver nanoparticles (Ag NPs) embedded in nanocomposites like gluten films with vitamins A and E have shown antibacterial and antioxidant properties.[78] Advanced wound dressings using herbal-extracted ZnO NPs also demonstrated dual antibacterial properties, enhancing healing.[79-80]

3.3. Cosmetic Applications

Nanoparticles, especially ZnO NPs, are widely used in sunscreens and skin care products for their UV protection capabilities.[81-83]

- **Safety Concerns:** While healthy skin has minimal NP penetration, damaged skin may allow increased absorption, potentially causing irritation or sensitization. Researchers advise cautious use of ZnO NPs in cosmetics.[84-85]

3.4. Antimicrobial Activity

ZnO NPs are effective against both Gram-positive and Gram-negative bacteria due to their ability to generate ROS and disrupt bacterial membranes.[86]

- **Green Synthesis:** Yang et al. synthesized antibacterial ZnO clusters via an eco-friendly process, enhancing bioactivity and bactericidal effects.[87-88]
- **Enhanced Formulations:** Sodium-doped ZnO NPs showed increased antibacterial and antifungal activities, while studies demonstrated mosquito control applications for dengue prevention.[89]

3.5. Biofilm Inhibition

Biofilms contribute to persistent infections on medical devices. ZnO NPs synthesized through green methods demonstrated significant biofilm destruction by disrupting microbial components.[90-91]

- **Improved Materials:** Tin-doped ZnO nanostructures exhibited superior antibiofilm activity, especially against *Staphylococcus aureus*, making them suitable for use in cosmetics and medical products.[92-93]

3.6. Environmental and Agricultural Applications

(a) Sustainable Farming

ZnO NPs, synthesized using endophytic bacteria, serve as biofertilizers, improving crop growth, protein content, and chlorophyll levels. Lime-waste-derived ZnO NPs also enhance agricultural yields and pest resistance.[94-96]

(b) Environmental Concerns

Excessive ZnO NP use poses risks to ecosystems. Studies reveal their toxic effects on aquatic life, soil bacteria, and plant growth. For example, ZnO NPs altered microbial populations in soil and reduced algae productivity, impacting aquatic food webs.[95-96]

3.7. Industrial Applications: Dye Removal

ZnO NPs are pivotal in wastewater treatment, particularly in adsorbing and degrading toxic dyes like Congo Red. Manganese-doped ZnO and composite materials demonstrated improved dye removal and cost-effective manufacturing processes.[97]

4. Biological/Green Synthesis Methods for ZnO - NPs

Biological synthesis, also referred to as "green synthesis," represents a promising and environmentally friendly alternative to conventional chemical and physical methods for nanoparticle (NP) production. Zinc oxide nanoparticles (ZnO-NPs) have historically been used in food additives, dietary supplements, and medicinal applications. This green approach employs safe reagents, such as water and natural extracts, avoiding hazardous chemicals and offering an innovative route for NP synthesis.[97-99] The advancements in nanobiotechnology have enabled the production of ZnO-NPs using biotechnological methods, presenting significant potential for medical applications.[100]

Biological pathways utilizing proteins, DNA, plants, or plant-derived extracts (e.g., roots, stems, leaves, flowers, and fruits) have been extensively explored as sustainable substitutes for chemical and physical synthesis methods.[101] These biological methods leverage the biochemical and enzymatic pathways in microorganisms to produce ZnO-NPs. For instance, proteins, amino acids, DNA, enzymes, phages, and marker genes in microorganisms play crucial roles. DNA, in particular, acts as a guiding framework for the controlled synthesis and growth of ZnO-NP chains.[102-103]

This biotechnological approach has demonstrated great promise in various biological applications, including bio-labeling, cell culture, gene delivery, drug delivery, and nanomedicine.[104]

4.1. Plant-Mediated Synthesis of ZnO-NPs

Plant-mediated synthesis is an eco-friendly alternative to traditional chemical methods, leveraging plants and their extracts for ZnO-NP production.[105] This method is appealing due to its simplicity, safety, and avoidance of harmful reagents. The process typically involves the following steps.

1. **Preparation of Plant Extracts**:
   - Selected plant materials (e.g., tomato fruits, chamomile flowers, olive leaves) are rinsed with double-distilled water and air-dried.[107]
   - The dried materials are ground into powder, and 200 mL of water is used to extract the bioactive compounds at 60–70°C for 4 hours.[108-109] Showing in Fig. 3.
   - The extract is then cooled to room temperature and filtered using filter paper.[110]

2. **ZnO-NP Synthesis**
   - The filtered plant extract is mixed with a zinc precursor (e.g., zinc acetate) in a reaction flask.
   - The mixture is stirred for 4 hours at 100 rpm under controlled heating conditions.[111-113]

3. **Purification of ZnO-NPs**
   - The reaction solution is centrifuged at 10,000×g for 20 minutes to separate the precipitate from the supernatant.
   - The precipitate is collected, washed with distilled water, and freeze-dried to obtain ZnO-NPs .[114]

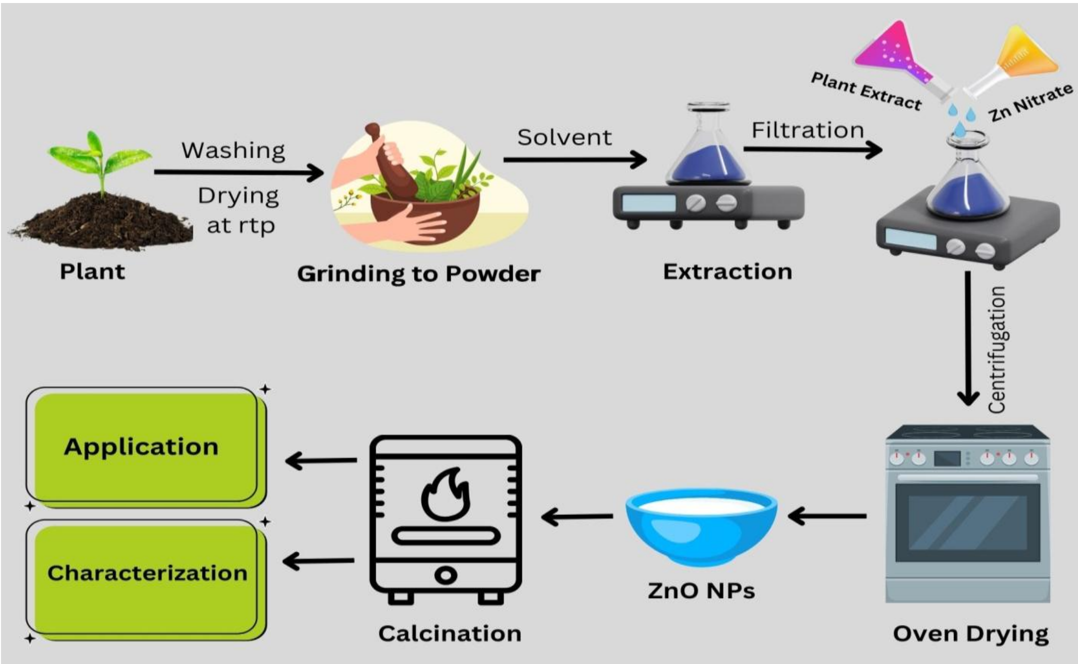

Figure 3: Biosynthesis of ZnO-NPs from Plant based extract.

5. Advantages of Advancements in ZnO Nanostructures

Advancements in ZnO nanostructures have unlocked numerous benefits in environmental and agricultural remediation.[115] Their remarkable photocatalytic properties enable efficient degradation of organic pollutants, dyes, and other hazardous substances, particularly under UV light.[116] This makes them a powerful tool for environmental cleanup efforts. ZnO nanostructures also exhibit broad-spectrum antimicrobial properties, which are invaluable for controlling plant pathogens and promoting crop health. Furthermore, their eco-friendly synthesis methods, including plant-mediated techniques, align with sustainable development goals by minimizing environmental harm. In agriculture, ZnO nanoparticles enhance soil fertility and nutrient uptake, fostering healthier plant growth.[117] Their versatility in form, such as nanoparticles, nanorods, and thin films, allows for tailored applications in diverse scenarios. Additionally, advancements in green synthesis have reduced production costs, making ZnO nanostructures more accessible for large-scale use.[118-120]

6. Disadvantages of Advancements in ZnO Nanostructures

Despite their potential, ZnO nanostructures face notable limitations. Environmental and ecological risks, such as nanoparticle toxicity to aquatic and terrestrial organisms, raise concerns about their long-term sustainability.[121] Moreover, their photocatalytic efficiency is primarily limited to UV light, reducing their effectiveness under natural sunlight unless modified through doping or other enhancements. Scaling up the production of ZnO nanostructures with uniform quality remains a challenge, especially in green synthesis methods.[122-123] Their tendency to agglomerate can further compromise efficiency, necessitating the use of stabilizers. Over-reliance on their antimicrobial properties in agriculture may lead to microbial resistance, diminishing their efficacy over time. Additionally, the lack of standardized regulatory frameworks and safety protocols complicates their deployment, highlighting the need for comprehensive assessments and guidelines to mitigate potential risks.

CONCLUSION

Advancements in ZnO nanostructures have demonstrated significant potential for addressing critical challenges in environmental and agricultural remediation. Their exceptional photocatalytic properties, antimicrobial activity, and ability to enhance nutrient uptake highlight their versatility and effectiveness. The development of green synthesis methods further reinforces their role as an eco-friendly and cost-effective solution. However, the associated challenges, including potential environmental toxicity, agglomeration issues, and limitations under natural light, underscore the importance of addressing these drawbacks through continued research and innovation. Moreover, the establishment of standardized safety protocols and regulatory frameworks is essential to ensure their responsible use. By striking a balance between maximizing benefits and mitigating risks, ZnO nanostructures can play a transformative role in fostering sustainable environmental and agricultural practices.[124]

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Authors' Contribution

Dr. Meet, collected all reviews and have prepared the contents in the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

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