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Metal oxide (Zinc oxide) Nanoparticles: Enhancing Photocatalytic and Antimicrobial function for Industrial wastewater treatment

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KEYWORDS

Antimicrobial Activities, hydrothermal, Industrial Wastewater, Photocatalytic, and Zinc Oxide Nanoparticles (ZnO)

ABSTRACT:

Among various nanomaterials, zinc oxide (ZnO) nanoparticles have gained considerable attention due to their exceptional physicochemical properties such as chemical stability, high surface area, and low toxicity. To break down organic pollutants and eliminate microbiological contaminants from industrial wastewater, this study looks into the photocatalytic and antibacterial properties of zinc oxide (ZnO) nanoparticles. Hydrothermal synthesis was used to create ZnO nanoparticles using two protocols using two precursors: zinc acetate dihydrate and Zinc(II) Nitrate Hexahydrate, and produced particles of size 300±10 nm and 600±15 nm. XRD confirmed the desired phase with minor impurities, and particle sizes matched Scherer's formula calculations. SEM also showed clear structure of ZnO type 1 and ZnO type 2. We checked these nanoparticles for their efficiency in removing several bacterial and fungal isolates. Significant inhibitory zones were seen at a dose of 100 mg/L for both types when ZnO nanoparticles were tested against bacterial strains (*Klebsiella pneumoniae*, *Pseudomonas aeruginosa*) and fungal species (*Aspergillus niger* and *Candida albicans*). Additionally, photocatalytic degradation of phenol and methylene blue (MB) under UV light exposure was assessed for both types of nanoparticles. We noted ZnO NP type 1 performed better in removing microbial contaminants, whereas ZnO type 2 was more efficient in removing organic pollutants. These findings show that ZnO nanoparticles produced by hydrothermal methods can improve water quality efficiently by eliminating organic and microbial contaminants highlighting their potential for environmental remediation applications.

1. Introduction

Recent progress within the area of nanotechnology, in particular, in synthesizing highly ordered nanoparticles by controlling their size and shape, offered new biocidal agents. This indeed can be called "a wonder of modern medicine." While some of the traditional antibiotics can act effectively against about half a dozen of the terrible pathogenic microorganisms, the nanomaterials can put out about 650 kinds of microbial cells [1]. As an alternative to antibiotics, inorganic metal nanoparticles have anti-inflammatory potential, which might be due to remarkable properties, such as optical, catalytic, electronic, and magnetic [2,3, 4]. The distinct properties of nanoparticles arise from variations in their dimensions, dispersal, and morphology. One of the most commonly used metal oxide nanoparticles is ZnO. It has large applications and is used in almost all fields, including optics, piezoelectric devices, magnetics, and gas sensing. The ZnO nanostructures are highly catalytic, possess high adsorption capacities, and are widely used in ceramics, sunscreens, wastewater treatment, rubber processing, and fungicides [5,6,7]. Notably, nZnO should be used more than nano-titanium dioxide in many applications in the market since nZnO could adsorb both the radiation in Ultraviolet-A and B, but $nTiO_2$ only blocks UV-B. This property gives excellent strength and improved characteristics of Opacity [6]. ZnO has a high value of exciton binding energy that is equal to 60 meV. This makes ZnO material that can stool a top UV lasing material at Ty temperature. ZnO was an efficient green luminescence with oxygen vacancies [8]. The contamination of industrial wastewater with organic pollutants and microbial pathogens poses significant environmental and public health challenges. Effective treatment methods are crucial to reduce the negative impacts of these contaminants on ecosystems and human health [9]. Among modern methods in water treatment, nanotechnology is regarded as one of the most response-bright remedies to provide valuable working methods for complications in pollution problems [10]. Due to the marked physicochemical properties, such as chemical stability, high surface area, and low toxicity, among diverse nanomaterials, the most attention has been paid to zinc oxide nanoparticles. The photocatalytic activity of ZnO is primarily ascribed to the ability to produce active oxygen species during illumination under ultraviolet light, adequate for the effective decomposition of organic pollutants into less toxic compounds [11, 12]. Further, the antimicrobial activity of ZnO NPs is contributed to even by the ability of ZnO NPs to disrupt cellular microbial membranes and evoke oxidative stress processes responsible for the inactivation of bacteria and fungi [13]. This study aims to explore the dual functionality of ZnO nanoparticles in degrading organic pollutants and removing microbial contaminants from industrial wastewater. The results of this research deliver valued understandings into the potential of ZnO nanoparticles as an efficient and sustainable solution for improving water quality in industrial settings.

2. Objectives

Enhancing Photocatalytic and Antimicribial Function for Industrial wastewater treatment, using zinc oxide (ZnO) nanoparticles. To break down organic pollutants and eliminate microbiological contaminants from industrial wastewater, this study looks into the photocatalytic and antibacterial properties of zinc oxide (ZnO) nanoparticles.

3. Materials and Methods

3.1 Zinc oxide nanoparticles synthesis

Hydrothermal synthesis of ZnO nanoparticles was carried out using. Stock solutions of zinc nitrate hexahydrate (0.1 M) were produced in methanol while stirring to generate ZnO nanoparticles [14]. These solutions were moved to a temperature 500ºC for five hours for calcination. Then it was allowed to cool to room temperature on its own accord Subsequently, it was allowed to cool. The saccharimeter reading was then taken naturally cooled to room temperature. Upon the determination of the reaction time, the flask’s contents were poured into a Büchner funnel where white solid end-products were filtered. The white solid end-products were washed with methanol and allowed to dry in a laboratory oven at 60ºC.

3.2 Characterization of ZnO Nanoparticles

3.2.1 X-ray Diffraction (XRD)

The crystalline structure and purity of the synthesized ZnO nanoparticles were characterized using XRD. The dried ZnO nanoparticles were finely ground and placed on a sample holder. The XRD patterns were obtained using a diffractometer with Nickel-filtered Cu Kα radiation (λ = 1.4506 Å) at 45 kV and 35 mA.

3.2.2 Scanning Electron Microscopy (SEM)

The morphological features and size distribution of the ZnO nanoparticles were analyzed using SEM. A small amount of the dried ZnO nanoparticles was dispersed in ethanol and ultrasonicated for 10 minutes to achieve a uniform suspension. A droplet of this suspension was kept on a silicon wafer and allowed to dry. The sample was then coated with a thin layer of gold to enhance conductivity and imaged using an SEM operated at an accelerating voltage of 20 kV.

3.3 Antimicrobial activity of ZnO nanoparticles

The antimicrobial activity of ZnO nanoparticles was assessed against bacterial strains *Staphylococcus aureus, Micrococcus luteus, Pseudomonas aeruginosa, Klebsiella pneumoniae,* and *Pseudomonas aeruginosa*, as well as fungi *Aspergillus flavus, Aspergillus niger, and Candida albicans*. The nanoparticles were dispersed in sterile deionized water to prepare a series of concentrations. Bacterial and fungal cultures were grown overnight in nutrient broth and Sabouraud dextrose broth, respectively. For the antibacterial assay, 100 µL of each bacterial suspension was spread uniformly on nutrient agar plates. Using a sterile cork borer, wells were punched into the agar and then filled with 50 µL of ZnO nanoparticle suspension. For twenty-four hours, the plates were incubated at 37°C. Through measurement of the diameter of the inhibitory zones surrounding the wells, antimicrobial activity was ascertained. For the antifungal assay, 100 µL of each

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fungal suspension was spread on Sabouraud dextrose agar plates. After punching the wells in the same way, 50 µL of ZnO nanoparticle suspension was added. For 48 hours, the plates were incubated at 28°C. Through measuring the diameter of the clear zones surrounding the wells, the antifungal activity was assessed.

3.4 Study of effectiveness of ZnO nanoparticles against contaminated water

For the microbial removal study, water samples were artificially contaminated with known concentrations of bacterial strains (*Pseudomonas aeruginosa*, *Klebsiella pneumoniae*) and fungal species (*Candida albicans* and *Aspergillus niger*). Different concentrations of ZnO nanoparticles (50 mg/L, 100 mg/L, 150 mg/L, and 200 mg/L) were added to separate contaminated water samples and stirred continuously for a contact time of 2 hours under ambient conditions. Control samples without ZnO nanoparticles were also prepared to assess the natural die-off rate of the microorganisms. Microbial counts were determined before and after treatment using the plate count method. On nutritional agar medium (for bacteria) and Sabouraud dextrose agar (for fungi), serial dilutions of treated and untreated samples were plated. The samples were then incubated at 37°C for 24 hours for bacterial cultures and at 30°C for 48 hours for fungal cultures. The number of colony-forming units (CFUs) was measured to estimate the decline in microbial populations.

3.5 Photocatalytic activity against organic pollutants:

The photocatalytic experiments were conducted by adding 100 mg/L of ZnO nanoparticles to the pollutant solutions methylene blue (MB) and phenol were evaluated. Control experiments without ZnO nanoparticles were also conducted to assess the photolytic degradation of the pollutants. The degradation of the pollutants was monitored by measuring the absorbance at specific wavelengths (665 nm for MB and 270 nm for phenol) using a UV-Vis spectrophotometer at regular intervals. The photocatalytic efficiency was determined by calculating the percentage reduction in the initial concentration of the pollutants.

4. Results and Discussion

4.1 ZnO nanoparticles Synthesis and characterization

Nanoparticles were synthesized based on the Bharti and Bharti method [14]. Nanoparticles synthesized by precursor zinc acetate dihydrate and from precursor Zinc(II) nitrate hexahydrate were called as Zno type 1 and ZnO type 2. The XRD pattern of the ZnO nanoparticles showed sharp and well-defined peaks, indicating a high degree of crystallinity. The diffraction peaks were indexed to the hexangular wurtzite structure of ZnO, with the most intense peaks corresponding to the (99), (102), and (105) planes. No additional peaks were observed, confirming the phase purity of the ZnO nanoparticles nm (Figure 1). The regular crystallite size was calculated using the Scherrer formula, which yielded a value of approximately 20. A similar result was seen by Islam et al [15]. ZnO nanoparticles were synthesized using two different methods, resulting in particle sizes of 300±10 nm and 600±15 nm, as determined by a particle size analyzer. XRD patterns of both samples confirmed the presence of the desired phase with minor impurities. The particle size measurements from the analyzer were corroborated by XRD using Scherer's formula. There were no significant agglomeration observed for nanoparticles type 1 and 2 suggesting effective dispersion and stability of the nanoparticles. The SEM images revealed that the ZnO nanoparticles were predominantly spherical and well-dispersed with a narrow size distribution. The average particle size was consistent with the XRD results, around 302±11 nm and 603±14 nm. SEM micrographs of the ZnO-1 sample indicated bit accumulation, whereas the ZnO-2 sample showed no such accumulation. The images also showed that the nanoparticles had smooth surfaces and uniform morphology, indicating good quality and homogeneity (Figure 2). These analyses highlight differences in thermal behavior and structural properties between the two ZnO nanoparticle samples. The results are in coordination with Bharti and Bharti study [14].

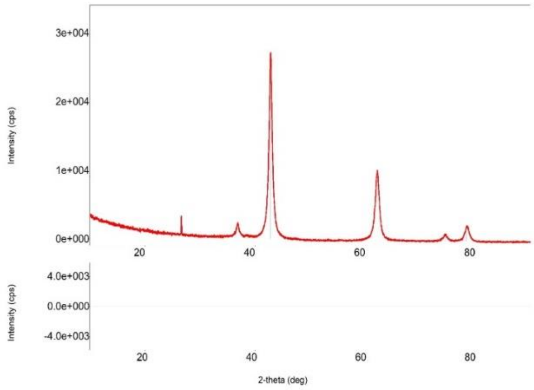

Figure 1: XRD pattern of ZnO nanoparticles.

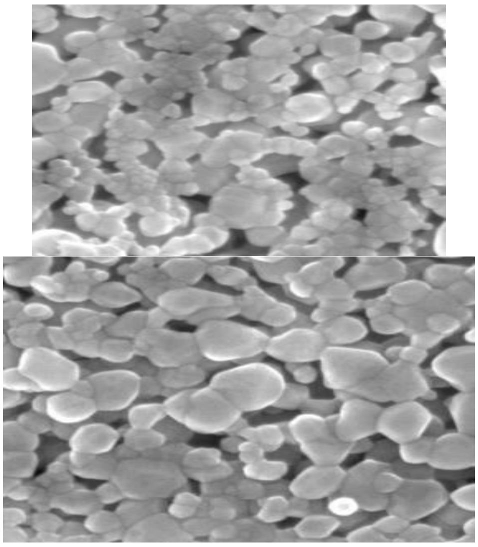

Figure 2: SEM analysis of ZnO synthesized from: a) zinc acetate dihydrate; b) Zinc(II) Nitrate Hexahydrate.

Figure 3: Inhibition zone of ZnO type 1 nanoparticles against *P. aeruginosa*.

Figure 4: Inhibition zones of type 1 nanoparticles against *K. pneumonia*.

Figure 5: Inhibition zones of type 2 nanoparticles against *C. albicans.*

Figure 6: Inhibition zones of type 2 nanoparticles against *A. niger*.

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4.2 Antimicrobial activity of ZnO nanoparticles

Clear inhibition zones were observed for both bacterial strains (*K. pneumoniae, P. aeruginosa*) and fungal species (*C. albicans* and *A. niger*) at a ZnO nanoparticle concentration of 100 mg/L. The average sizes of the inhibition zones for *K. pneumoniae, P. aeruginosa, A. niger and C. albicans* were measured. It was18 mm, 22mm, 16mm and 20mm respectively for ZnO type 1 nanoparticles and 21mm, 18.5mm, 17.5mm and 22mm for ZnO type 2 nanoparticles (Figure 3-6). These inhibition zones indicate a significant antimicrobial activity of ZnO nanoparticles against both bacterial and fungal species. The results suggest that ZnO nanoparticles are effective in creating a hostile environment for these microorganisms, leading to their substantial reduction. The mechanism of antimicrobial activity is likely due to the generation of reactive oxygen species (ROS) by the ZnO nanoparticles, which can damage microbial cell membranes, proteins, and DNA. Additionally, the small size of the nanoparticles allows for better penetration and interaction with microbial cells, enhancing their antimicrobial efficacy [16, 17].

4.3 Photocatalytic activity against organic pollutants:

The synthesized ZnO nanoparticles type 1 and type 2 showed high reactivity against the organic pollutants. We noted methylene blue degradation efficiency was 95% and 89%under 120 min of UV irradiation, analyzed by the decrease in absorbance that occurred at the wavelength of 665 nm. Similarly, phenol degradation was up to 85%, and 81% indicated by an absorbance decrease at 270 nm. In contrast, control runs without ZnO nanoparticles exhibited minimal degradation of the pollutant, thus confirming that the prime role of photocatalysis remains with ZnO nanoparticles. High photocatalytic efficiency was believed to result from generating reactive oxygen species, such as hydroxyl radicals and superoxide anions when ZnO nanoparticles interact with water under UV illumination. ROS attacks organic pollutant molecules and mineralizes them through degradation into smaller parts [18]. Hence, it can be seen that removing organic pollutants in water is possible with ZnO nanoparticles, which represent it as an active photocatalyst. Due to the potent antimicrobial properties and photocatalytic activity of ZnO nanoparticles, they are used in sewage wastewater management. Additionally, ZnO nanoparticles can possible degradation of organic pollutants present in sewage through photocatalysis [19]. The ZnO nanoparticles, in turn, create electron-hole pairs with the effect of UV light—these create ROS, and ROS, on the other hand, can degrade organic molecules to less harmful ones [20]. Apart from this, the formation of ROS due to the effect of light inactivates the cellular constituents of the microorganisms. Disruption of the microbial cell membrane might also result from the surface charge and morphology of the nanoparticles used [21].

5. Conclusion

The present study concludes that ZnO NPs produced by the hydrothermal method can be a promising candidate usable in industrial wastewater management. We noted ZnO NP type 1 performed better in removing microbial contaminants, whereas ZnO type 2 was more efficient in removing organic pollutants. Future studies toward practical implementation and evaluation of the environmental impact of this method will provide a cheap method for the practicability of these nanoparticles in industrial water management.

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