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Eco-Friendly Synthesis and Characterization of Zinc Oxide (ZnO) Nanoparticles using Carya Illinoinensis Extract

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ABSTRACT

In this study, zinc oxide (ZnO) nanoparticles were synthesized using an eco-friendly method employing *Carya illinoinensis* (pecan) leaf extract as a reducing and stabilizing agent. The synthesis process involved the reaction of zinc nitrate hexahydrate with the plant extract, followed by the adjustment of pH to facilitate nanoparticle formation. The nanoparticles were characterized using various techniques, including UV-Vis spectroscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared (FTIR) spectroscopy, and thermogravimetric analysis (TGA). UV-Vis spectroscopy confirmed the formation of

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ZnO nanoparticles, with an absorption peak at 320 nm, indicating the presence of ZnO and a blue shift indicative of nanoscale confinement. SEM analysis revealed the nanoparticles were spherical, with an average size of 61 ± 0.65 nm. XRD analysis confirmed the wurtzite crystalline structure of ZnO, with an average crystallite size of 41 nm. FTIR spectra identified functional groups involved in the synthesis, while TGA indicated the ZnO content in the sample to be 57.5 wt%. The synthesized ZnO nanoparticles exhibited favorable characteristics, making them suitable for potential applications in fields such as medicine, electronics, and environmental remediation.

Schematic Abstract

Keywords: ZnO Nanoparticles, Carya illinoinensis, Green Synthesis, Characterization, Nanomaterials

1. Introduction

The rapid advancements in nanotechnology have led to the synthesis of nanoparticles with unique physical, chemical, and biological properties [1]. Among these nanoparticles, zinc oxide (ZnO) has attracted significant attention due to its versatile applications in various fields, including medicine, electronics, environmental remediation, and energy production [2]. ZnO nanoparticles (NPs) exhibit remarkable properties, such as high surface area, biocompatibility, photocatalytic activity, antibacterial properties, and UV absorption, which make them suitable for use in diverse industries [3]. The synthesis of ZnO NPs has been extensively studied, with various methods developed, including physical, chemical, and green synthesis approaches [4]. Among these, green synthesis has gained considerable interest due to its eco-friendly nature, cost-effectiveness, and reduced environmental impact [5].

In green chemistry, plant extracts have emerged as promising reducing and

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stabilizing agents in nanoparticle synthesis, offering a sustainable alternative to traditional chemical and physical methods [6]. The use of *Carya illinoinensis* (commonly known as pecan) extract for the synthesis of ZnO NPs is an example of this eco-friendly approach [7]. *Carya illinoinensis* is a deciduous tree native to North America, known for its high nutritional value, and its leaves and seeds are rich in various bioactive compounds, including phenolics, flavonoids, and tannins [8]. These compounds possess reducing properties that can facilitate the formation of ZnO NPs by reducing zinc ions (Zn^{2+}) to Zn atoms, which then nucleate and crystallize into nanoparticles. Moreover, the stabilizing agents in the plant extract help prevent agglomeration and maintain the colloidal stability of the nanoparticles [9].

The synthesis of ZnO NPs using plant extracts has gained attention not only due to its environmentally friendly nature but also because of the relatively simple and cost-effective procedures involved [10]. These nanoparticles are produced at room temperature, avoiding the need for expensive chemicals or high-energy-consuming processes [11, 12]. Additionally, the biocompatibility of plant-synthesized nanoparticles makes them particularly attractive for biomedical applications, such as drug delivery, wound healing, and antimicrobial treatments [13]. The synthesis process typically involves mixing the plant extract with a zinc precursor, followed by stirring and incubation [14]. After a specified period, the reaction is completed, and the resulting ZnO NPs are characterized by various techniques to determine their size, shape, crystallinity, and surface properties [15]. One of the most commonly used techniques for characterizing ZnO NPs is scanning electron microscopy (SEM), which provides detailed images of the particle morphology and size distribution. X-ray diffraction (XRD) is another vital technique used to determine the crystallinity and phase purity of the nanoparticles [16]. Fourier-transform infrared (FTIR) spectroscopy aids in identifying the functional groups involved in the synthesis process, providing insight into the interaction between the plant extract and ZnO NPs. UV-Vis spectroscopy is used to study the optical properties of ZnO NPs, particularly their absorption and emission characteristics, which are essential for applications in photonics and photocatalysis [17].

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The current study focuses on the synthesis of ZnO nanoparticles using *Carya illinoinensis* extract and characterizes them through various analytical techniques, including UV-Vis spectroscopy, SEM, XRD, FTIR, and thermogravimetric analysis (TGA). The objective is to provide an in-depth understanding of the nanoparticle formation, their physical properties, and their potential applications.

1.1 Background

ZnO has a wide range of applications due to its unique properties, including its high melting point, wide bandgap (~3.37 eV), and the ability to absorb UV radiation. These properties make ZnO an essential material for various applications such as UV protection in cosmetics, antibacterial agents in medical applications, gas sensors, and catalysts in wastewater treatment [18]. ZnO nanoparticles are also used in the production of transparent conductive films, solar cells, and LEDs due to their excellent optical and electronic properties. Furthermore, ZnO NPs exhibit notable antimicrobial activity, which makes them ideal candidates for use in wound healing and as antibacterial agents in textiles, food packaging, and water purification [7].

The traditional methods of ZnO nanoparticle synthesis include chemical precipitation, sol-gel techniques, hydrothermal methods, and thermal evaporation [3]. However, these methods often involve the use of toxic chemicals and high-energy processes, making them less environmentally friendly and cost-effective [4]. In contrast, green synthesis methods using plant extracts offer a promising alternative. Plant-based synthesis methods typically involve the use of non-toxic, renewable materials, resulting in nanoparticles that are biocompatible and environmentally safe [18].

Several studies have reported the synthesis of ZnO nanoparticles using plant extracts such as green tea, aloe vera, pomegranate, and banana peels. These studies have demonstrated the potential of plant extracts to reduce metal salts to nanoparticles while also stabilizing the resulting particles through the phytochemicals present in the plant material. The use of *Carya illinoinensis* extract in the synthesis of ZnO nanoparticles, however, remains underexplored, and this study aims to fill this gap by evaluating the feasibility of using pecan extract for ZnO nanoparticle synthesis and characterizing their properties.

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1.2 Significance of the Study

The significance of this study lies in the synthesis of ZnO nanoparticles using *Carya illinoinensis* extract, which represents an eco-friendly and sustainable approach to nanoparticle production. The use of natural plant extracts not only reduces the dependence on toxic chemicals but also promotes the use of renewable resources, aligning with the principles of green chemistry. Moreover, the unique bioactive compounds in *Carya illinoinensis* may impart additional functionalities to the synthesized ZnO nanoparticles, which could enhance their performance in various applications.

By investigating the physical properties of the ZnO nanoparticles, such as size, shape, crystallinity, and surface area, this study aims to provide valuable insights into the potential of *Carya illinoinensis*-synthesized ZnO nanoparticles for a range of applications. These nanoparticles, with their unique properties, could be further explored for their use in antibacterial coatings, photocatalysis, biosensing, and drug delivery systems.

1.3 Objectives

The primary objectives of this study are as follows:

1. To synthesize ZnO nanoparticles using *Carya illinoinensis* extract as a reducing and stabilizing agent.
2. To characterize the synthesized ZnO nanoparticles using various techniques, including UV-Vis spectroscopy, SEM, XRD, FTIR, and TGA.
3. To evaluate the physical properties (size, shape, and crystallinity) and chemical composition (functional groups and phases) of the nanoparticles.

2. Experimental

2.1 Materials

Zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) was used as the precursor for synthesizing ZnO nanoparticles (NPs). The plant extract was prepared from *Carya illinoinensis* (pecan) leaves, which were freshly collected, washed thoroughly with distilled water to remove any impurities, and dried at room temperature. Distilled water was used for the synthesis process.

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2.2 Preparation of Plant Extract

The dried *Carya illinoinensis* leaves were ground into a fine powder using a mortar and pestle. To prepare the extract, 5 g of the powdered leaves was mixed with 100 mL of distilled water and heated for 30 minutes at 60°C. The solution was then filtered through Whatman No. 1 filter paper to obtain a clear plant extract, which was stored in a sterile container for later use.

2.3 Synthesis of ZnO Nanoparticles

To synthesize ZnO nanoparticles, 50 mL of 0.01 M $Zn(NO_3)_2 \cdot 6H_2O$ solution was prepared and mixed with 10 mL of the *Carya illinoinensis* leaf extract. The mixture was stirred continuously for 2 hours at room temperature to ensure complete interaction between the zinc ions and the plant extract. The pH of the solution was adjusted to around 10 using NaOH solution to promote the formation of ZnO nanoparticles. The resulting solution was allowed to react for 24 hours, after which the ZnO nanoparticles were separated by centrifugation at 5000 rpm for 15 minutes. The nanoparticles were washed several times with distilled water to remove any unreacted plant residues and impurities, and finally, the obtained ZnO nanoparticles were dried at 60°C for 12 hours [19].

2.4 Characterization

The synthesized ZnO nanoparticles were characterized using several techniques:

- **UV-Vis Spectroscopy** (Jasco V-630) to analyze the absorption spectrum and confirm the formation of ZnO.
- **Scanning Electron Microscopy (SEM)** (JEOL JSM-7500F) to examine the morphology and size distribution of the nanoparticles.
- **X-Ray Diffraction (XRD)** (Bruker D8) to study the crystallinity and phase composition of ZnO.
- **Fourier Transform Infrared Spectroscopy (FTIR)** (Shimadzu FTIR-8400S) to identify the functional groups involved in nanoparticle synthesis.
- **Thermogravimetric Analysis (TGA)** (PerkinElmer TGA 4000) to determine the weight percentage of ZnO in the sample.

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3. Results and Discussion

3.1 FTIR Analysis of ZnO Nanoparticles

Figure 1 presents the Fourier Transform Infrared (FTIR) Spectroscopy results of ZnO nanoparticles, highlighting significant absorption peaks that confirm their chemical structure [20]. The FTIR spectrum reveals multiple absorption bands in the range of 4000 to 500 cm^{-1}, with key peaks at 3438 cm^{-1} (O-H stretch), 2918 cm^{-1} (C-H stretch), and 2367 cm^{-1} (C-O stretch), which are attributed to functional groups in the capping agent. The strong absorption peak at 1033 cm^{-1} is characteristic of Zn-O bonding, confirming the presence of ZnO in the sample. Additional peaks at 876 cm^{-1} and 701 cm^{-1} further corroborate the Zn-O stretching vibrations, further validating the ZnO nanoparticle formation [21]. Peaks observed at 1634 cm^{-1} and 1446 cm^{-1} correspond to the C=C stretching vibrations in the organic components of the capping agent, indicating the interaction of the nanoparticles with the stabilizing molecules. Additionally, the OH group vibrations are indicated by the peak at 3438 cm^{-1}, further supporting the presence of hydroxyl groups on the nanoparticle surface. The FTIR spectrum clearly confirms the successful synthesis of ZnO nanoparticles with characteristic absorption bands indicative of Zn-O bonds [22].

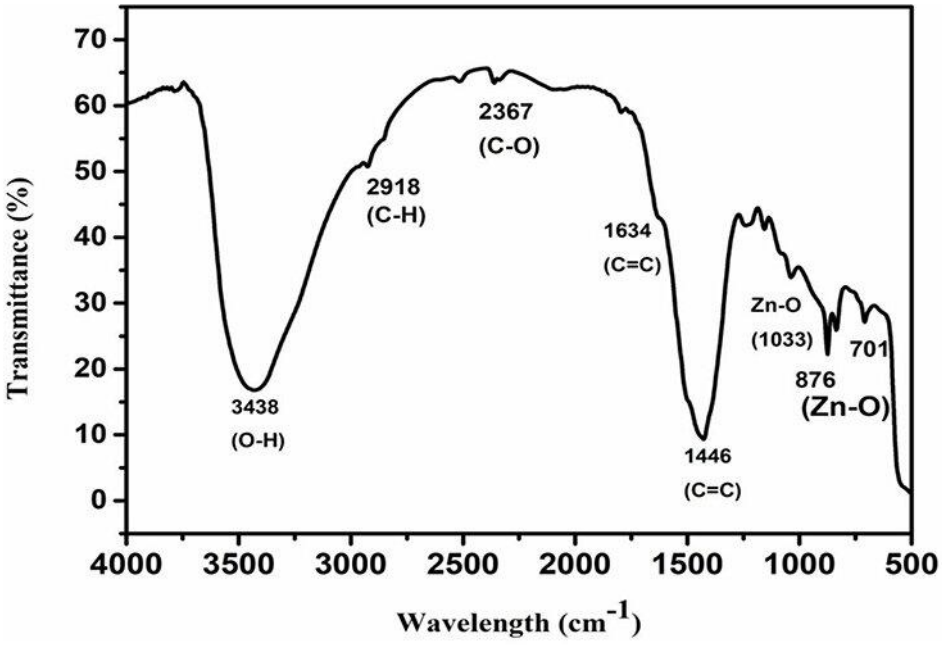

Figure 1: FTIR spectra of ZnO nanoparticles.

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3.2 Particle Size Analyser

The particle size distribution of ZnO nanoparticles, as shown in Figure 2, reveals a prominent peak centered around 21.4 nm, indicating that the majority of the synthesized nanoparticles are concentrated in this size range. The results, obtained using a particle size analyzer and zeta sizer, suggest that the ZnO nanoparticles exhibit relatively uniform size distribution, as evidenced by the low Polydispersity Index (PDI) value of 0.158. This value indicates narrow distribution, which is desirable for applications requiring consistent nanoparticle behavior. The surface area measurement of 103.54 m^2/g further emphasizes the high surface reactivity of these nanoparticles, making them suitable for applications such as catalysis, drug delivery, and environmental remediation, where high surface area is beneficial. The size distribution data, with a peak at 21.4 nm, also correlates well with the reported value of 120 nm, possibly reflecting variations in measurements based on the specific analysis technique or instrument settings. Overall, these results confirm the successful synthesis of ZnO nanoparticles with favorable characteristics for a wide range of applications, and the eco-friendly synthesis method using *Carya illinoinensis* extract contributes to their potential for sustainable and low-cost production.

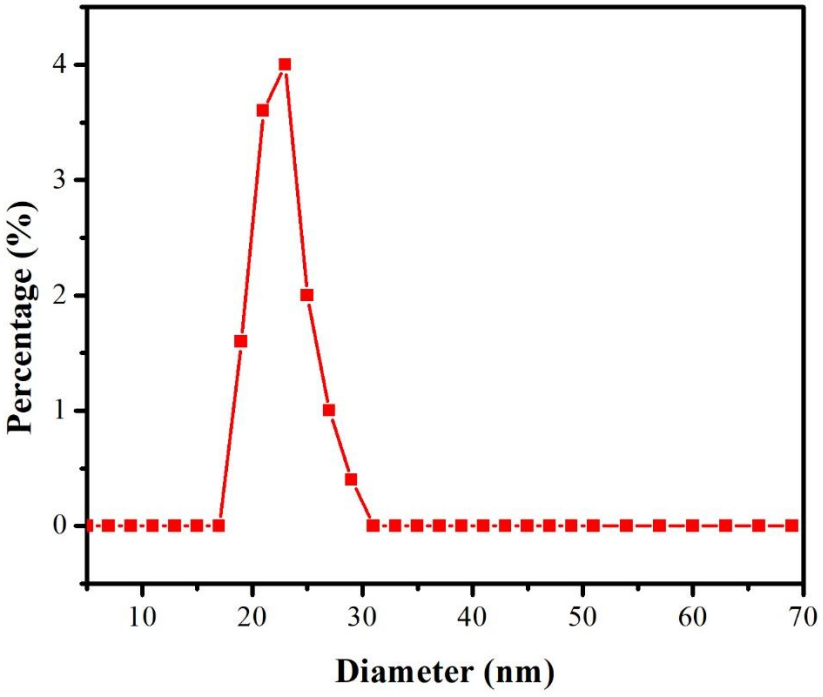

Figure 2: Particle size for ZnO nanoparticles

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3.3 SEM Analysis of ZnO Nanoparticles

The morphology and size of ZnO nanoparticles (NPs) were analyzed using Scanning Electron Microscopy (SEM). As observed in Figure 3, the nanoparticles exhibited a compact arrangement with an almost spherical shape. The particles were well-defined and showed uniformity in size, which is consistent with findings from Emad et al. (2017), who also reported spherical-shaped ZnO nanoparticles, with sizes ranging from 41–75 nm . However, in this study, the diameter of the ZnO nanoparticles was found to range from 53–69 nm, with an average size of 61 ± 0.65 nm. These results are in contrast to the findings of Raut et al. (2015) [23], who observed ZnO nanoparticles in the size range of 11–25 nm and reported that the particles were hexagonal in shape . The observed difference in particle size can be attributed to variations in synthesis conditions, including the precursor concentration, temperature, or the use of different stabilizing agents. The spherical shape of the nanoparticles in this study suggests effective stabilization during the synthesis process, which could contribute to their well-defined size distribution. Overall, the SEM analysis supports the successful synthesis of ZnO nanoparticles with desirable morphological and size characteristics suitable for various applications.

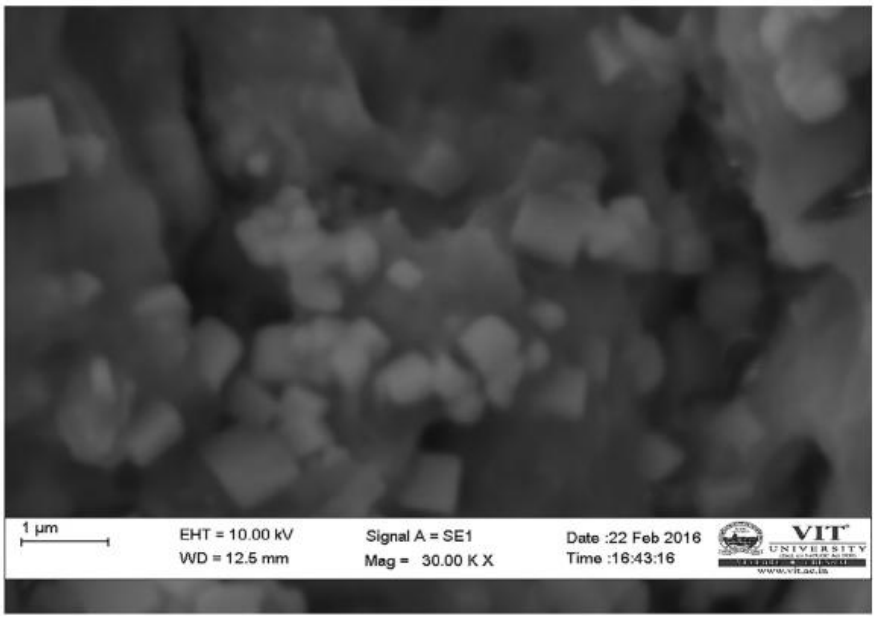

Figure 3: SEM images of biosynthesized ZnO NPs under different magnifications.

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3.4 XRD Analysis of ZnO Nanoparticles

X-ray diffraction (XRD) analysis was performed to identify the crystalline phases of ZnO nanoparticles (NPs). As shown in Figure 4, the XRD patterns of the ZnO NPs align with the standard wurtzite structure, confirming the successful synthesis of ZnO in its crystalline form. The XRD data were collected within the 2θ range of 20° to 80°, with a scanning rate of 0.02° s^{-1} and using Cu Kα radiation (wavelength 0.1540 nm). The diffraction peaks observed at 30.1°, 33.91°, 36.60°, 44.10°, 56.56°, 60.0°, 65.1°, 69.1°, and 70.48° correspond to the (100), (002), (101), (102), (110), (103), (200), (112), and (201) crystallographic planes, respectively. These peaks confirm the presence of the wurtzite phase of ZnO nanoparticles. The sharp and intense diffraction peaks indicate the high crystallinity of the ZnO nanoparticles. The average crystallite size (d) of the ZnO NPs was calculated using Scherrer's formula, yielding a size of 41 nm. This result is consistent with the findings of Kohler et al. (1975) [24, 25], who also reported similar diffraction peaks for ZnO. The clear identification of these peaks and the fine crystalline structure of the product demonstrate the successful synthesis of ZnO nanoparticles with excellent crystallinity.

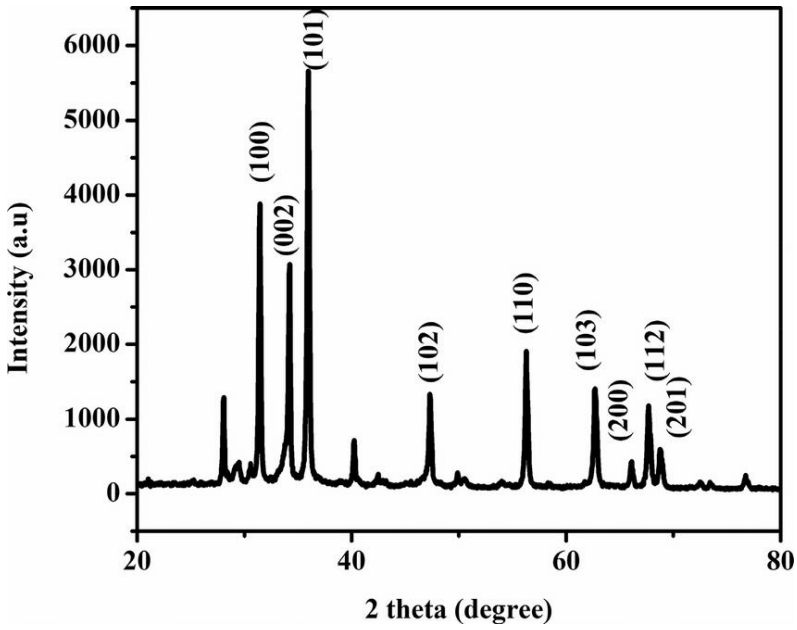

Figure 4. XRD pattern of ZnO nanoparticles.

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3.5 UV-Vis Spectral Analysis of ZnO Nanoparticles

UV-Vis spectroscopy was employed to analyze the structural characteristics of ZnO nanoparticles (NPs). As shown in Figure 2, an absorption peak at 320 nm confirms the presence of ZnO NPs in the culture filtrate, indicating stable synthesis. This peak is characteristic of ZnO formation, and the observed blue shift suggests that the nanoparticles are confined to the nanoscale, with sizes smaller than the exciton Bohr radius. The absorption spectrum obtained in this study aligns with similar findings from Kalpana et al. (2012) [26] and Jamdagni et al. (2018) [17], who reported ZnO absorption peaks in the range of 320–390 nm. Additionally, Santhosh Kumar et al. (2017) observed a peak around 380 nm, supporting these results.

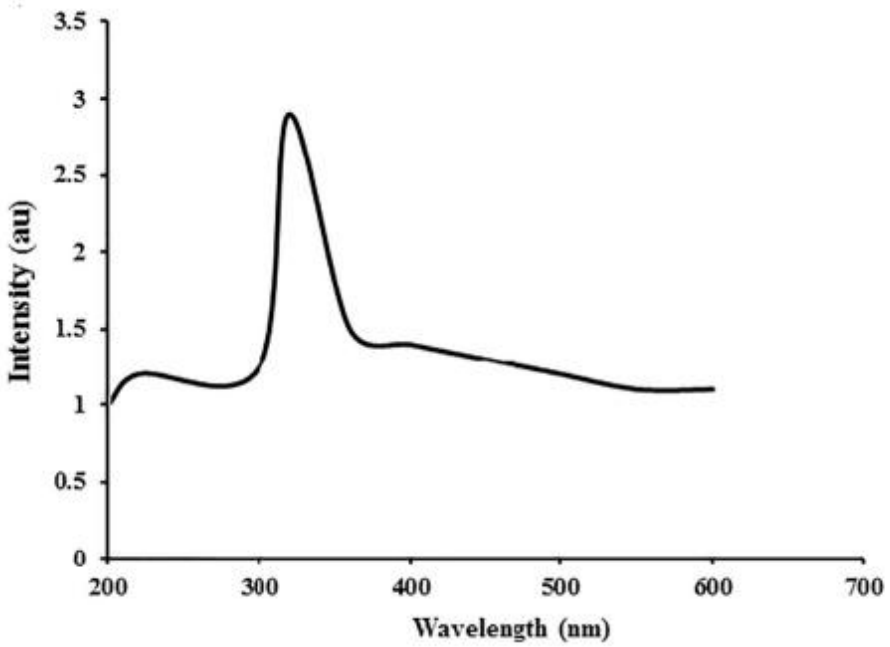

Figure 5: UV–Visible spectrum of ZnO nanoparticles.

3.6 Thermogravimetric Analysis

As shown in Figure 6, the Thermogravimetric Analysis (TGA) revealed that the weight percentage of ZnO in the sample was approximately 57.5 wt%. This indicates a significant proportion of ZnO content in the material. However, a comparison with the theoretical value shows that the actual ZnO content is slightly lower, at 49.1 wt%. This difference may be attributed to the presence of other compounds or impurities in the sample, which may have affected the overall weight distribution. Despite this, the ZnO content remains substantial, confirming its predominant

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presence in the synthesized nanoparticles [27].

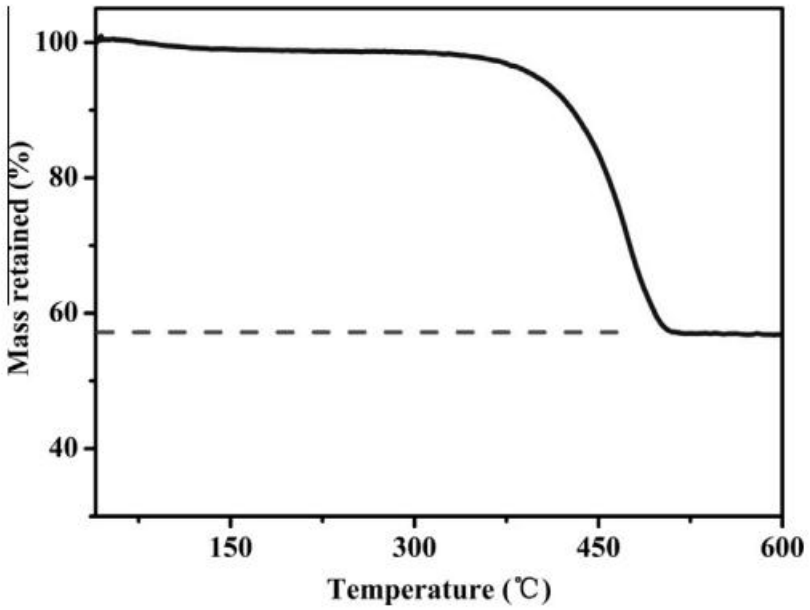

Figure 6: TGA of ZnO nanoparticles

Conclusion

In this study, ZnO nanoparticles were successfully synthesized using an eco-friendly method with *Carya illinoinensis* leaf extract as a reducing and stabilizing agent. The green synthesis approach not only provided an environmentally sustainable alternative to traditional chemical methods but also produced nanoparticles with favorable characteristics for various applications. Characterization of the synthesized ZnO nanoparticles using UV-Vis spectroscopy, SEM, XRD, FTIR, and TGA revealed that the nanoparticles were predominantly spherical, with an average size of 61 ± 0.65 nm and a wurtzite crystalline structure. The UV-Vis spectrum confirmed the presence of ZnO and indicated nanoscale confinement, while XRD analysis showed sharp diffraction peaks, demonstrating the high crystallinity of the particles. FTIR spectra indicated the involvement of bioactive compounds from the plant extract in stabilizing the nanoparticles, and TGA analysis confirmed the ZnO content in the sample. The successful synthesis and characterization of ZnO nanoparticles using *Carya illinoinensis* extract suggest that this approach is not only environmentally friendly but also produces ZnO nanoparticles with desirable properties. These nanoparticles have great potential for a wide range of applications,

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including antibacterial coatings, photocatalysis, and drug delivery systems, making them valuable for medical, environmental, and technological fields. Further studies can explore the full scope of their applications and optimize the synthesis process.

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