

# Sustainable Synthesis of Zinc Oxide Nanomaterials Via Plant-Mediated Methods

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## ABSTRACT

Green nanoparticle synthesis has emerged as a sustainable and environmentally benign approach for the production of metal and metal oxide nanoparticles. Unlike conventional physical and chemical methods that involve toxic reagents, high energy consumption, and hazardous byproducts, green synthesis utilizes biological resources such as plant extracts, microorganisms, and biomolecules as reducing and stabilizing agents. Plant-mediated synthesis is particularly advantageous due to its simplicity, cost-effectiveness, scalability, and rapid reaction kinetics. Phytochemicals including flavonoids, phenolics, alkaloids, proteins, and carbohydrates play a crucial role in the reduction of metal ions and stabilization of the formed nanoparticles through functional groups such as hydroxyl, carbonyl, and amine groups. The integration of green chemistry principles with nanotechnology not only minimizes environmental impact but also promotes the development of sustainable materials for industrial applications. The present study reports the green synthesis and biological applications of zinc nanoparticles (ZnNPs) using Terminalia arjuna leaf extract. The synthesized ZnNPs were characterized using UV-Visible spectroscopy and FTIR analyses to confirm their formation, functional groups involvement, crystalline nature, and surface morphology. The UV-Vis spectra showed a characteristic absorption peak confirming nanoparticle formation, while FTIR analysis indicated the participation of bioactive functional groups in reduction and stabilization. Antioxidant assay of the synthesized zinc nanoparticle showed 65% of inhibition at 10  $\mu$ L concentration. Antibacterial activity of the green nanoparticle showed greater zone of inhibition against both Gram – positive and Gram-negative bacterial strains. The synthesized green zinc oxide nanoparticles offer safer and sustainable alternatives for biomedical applications.

**Keywords:** Green nanoparticle, Metal oxide, Phytochemicals, Sustainable materials

## 1.INTRODUCTION

Nanotechnology deals with the manipulation of materials at the nanoscale (1–100 nm), where materials show unique physical, chemical, and biological properties due to their high surface area and quantum effects. Among various nanomaterials, zinc oxide nanoparticles (ZnO NPs) are widely studied because of their optical, catalytic, and antimicrobial properties.<sup>[1]</sup> They are used in applications such as sensors, drug delivery, photocatalysis, agriculture, environmental remediation, and biomedical fields due to their stability, low cost, and multifunctional nature. Nanoparticles can be synthesized using physical, chemical, and biological methods. However, conventional methods often require high temperature, expensive equipment, and toxic chemicals, which may cause environmental and health risks.<sup>[2]</sup> To overcome these issues, green synthesis has emerged as an eco-friendly alternative that uses biological resources such as plant extracts, bacteria, fungi, and algae. Plant-mediated synthesis is widely used because plant extracts contain phytochemicals that act as reducing and stabilizing agents during nanoparticle formation. This method is cost-effective, environmentally friendly, and produces nanoparticles with better stability and biocompatibility. As a result, green synthesized ZnO nanoparticles have gained significant attention for applications in medicine, agriculture, environmental protection, and industry.<sup>[3]</sup>

## 2.EXPERIMENTAL

### 2.1.MATERIALS

#### 2.1.1. Preparation of *terminalia arjuna* leaf extract

The fresh leaves of *terminalia arjuna* were washed with distilled water and dried under the shade. After drying, the leaves were made into fine powder using mechanical blender and transferred into an air tight container. Accurately 25 g of powdered *terminalia arjuna* leaves were weighed out and added to 500 ml distilled water in 400 ml beaker and heated for about 15-20 minutes. The solution is kept aside for settle and filtered.



*Terminalia arjuna* leaves



Powdered leaf sample



Preparation of *terminalia arjuna* extract leaf



### 2.1.2. Green synthesis of Zinc Oxide nanoparticles

About 3g of Zn (NO<sub>3</sub>)<sub>2</sub> · 6H<sub>2</sub>O was dissolved in 25 ml of Plant extract with constant stirring. Then the mixture was placed in a magnetic stirrer at ambient temperature for one hour, until a precipitate is formed. The formation precipitate indicates the formation of Zinc oxide nano particle. The solution was dried and used for the characterization of Zinc oxide nano particle.



Preparation of ZnO NPs



Zinc Oxide

## 2.2. METHODS

### 2.2.1. UV-Visible spectroscopy

The most important and simple technique for conforming the formation of nanoparticles is ultraviolet spectroscopy. Ultraviolet-visible spectroscopy or ultraviolet spectrophotometer involves the spectroscopy of photons in the UV-Visible region. The pure Zinc oxide nanoparticles were monitored by measuring the UV-Visible spectrometer by diluting a small aliquot of the sample into ethanol.<sup>[4]</sup> UV Vis spectroscopic analysis of zinc oxide nanoparticle synthesized from terminalia arjuna was performed at Avinashi lingam Institute of home science and Higher Education for Women (Bharat Ratna prof. CNR Rao research Centre), Coimbatore.

### 2.2.2. FT-IR Analysis

The functional group present in the sample was recorded using Fourier transform infrared spectroscopy. In FTIR Spectroscopy, the light is directed onto the sample of interest, and the intensity is measured using an infrared detector.<sup>[5]</sup> FTIR analysis of green synthesized zinc oxide nanoparticle was performed at Avinashi lingam Institute of Home Science and Higher Education for Women (Bharat Ratna prof. CNR Rao research Centre), Coimbatore.

### 2.2.3. X-Ray Diffraction Analysis

The crystalline nature of the synthesized zinc oxide nanoparticle was analyzed using X-ray diffraction. X-ray diffraction, a phenomenon in which the atoms of a crystal, by virtue of their uniform spacing, cause an interference pattern of the waves present in an incident beam of X rays. The atomic planes of the crystal act on the X-rays in exactly the same manner as does a uniformly ruled diffraction grating on a beam of light. The average crystalline equation size of nickel oxide nanoparticles was calculated using the Debye Scherrer's equation.<sup>[6]</sup>

### 2.2.4. SEM Analysis:

The morphological characteristics of the synthesized ZnO nanoparticles were analyzed using Scanning Electron Microscopy (SEM). The nanoparticles were coated with a thin layer of gold to enhance conductivity before imaging. SEM micrographs were obtained at different magnifications to observe the surface morphology, particle size, and agglomeration behavior of the nanoparticles.<sup>[7]</sup> The SEM Analysis of green synthesized nanoparticle was performed at

Avinashi lingam Institute of Home Science and Higher Education for Women (Bharat Ratna prof. CNR Rao research Centre), Coimbatore.

### 2.3. BIOLOGICAL ACTIVITY:

#### 2.3.1. Anti-oxidant assay

Antioxidant assays of zinc oxide (ZnO) nanoparticles synthesized using terminalia arjuna leaf extract are performed to evaluate their ability to neutralize free radicals and prevent oxidative damage. The plant extract acts as both a reducing and stabilizing agent during nanoparticle synthesis, enriching the ZnO nanoparticles with natural phytochemicals such as flavonoids, phenolics, and alkaloids. These bioactive compounds enhance the antioxidant potential of the nanoparticles, making them more effective compared to chemically synthesized ZnO nanoparticles.<sup>[8]</sup> It was done at Avinashi lingam Institute of Home Science and Higher Education for Women (Bharat Ratna prof. CNR Rao research Centre), Coimbatore.

#### 2.3.2. Antimicrobial activity

An antibacterial study of ZnO NPs from leaf extract was performed using the agar-well diffusion method against *Staphylococcus aureus* and *Escherichia coli*. The antimicrobials present in the test samples are allowed to diffuse out into the medium and interact in a plate freshly seeded with the test organisms. The resulting zones of inhibition will be uniformly circular as there will be a confluent lawn of growth.<sup>[9]</sup> The diameter of zone of inhibition can be measured in millimeters. Petriplates containing 20 ml Mueller Hinton medium were seeded with 0.5 McFarland standard cultures of bacterial strains. Wells were cut using sterile well puncture and 50  $\mu$ l of samples were added into the wells. Chloramphenicol is used as the positive control. The plates were then incubated at 37°C for 24 hours. The antibacterial activity was assayed by measuring the diameter of the inhibition zone formed around the well.<sup>[10]</sup> Antimicrobial activity was performed at Avinashilingam Institute of Home Science and Higher Education for Women (Microbiology research centre), Coimbatore.

### 3. Result and discussion

#### 3.1. UV-Visible Spectroscopy

The UV-Visible spectrum of the prepared ZnO nanoparticles shows strong absorbance in the ultraviolet region with a major peak at 232 nm (OD = 1.007). Smaller peaks are observed at 251 nm (OD = 0.067) and 290–292 nm (OD = 0.024–0.026). This UV absorption is mainly due to the band gap transition, where electrons move from the valence band to the conduction band in ZnO. The sharp absorption edge indicates the formation of nanosized ZnO particles, while

the absence of absorption in the visible region suggests that the nanoparticles are pure, well-structured, and show minimal aggregation<sup>[11]</sup>

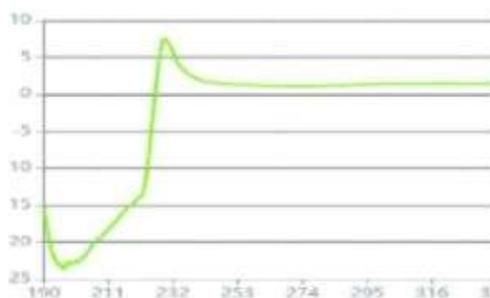
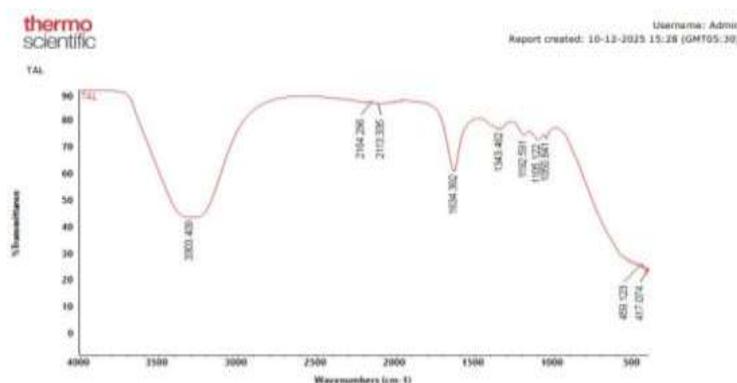


Figure 1. UV-Visible Spectroscopy of ZnO

### 3.2.FT-IR Analysis

The FTIR spectrum of the TAL-Zn sample shows several peaks confirming the formation of ZnO nanoparticles and the presence of organic stabilizing molecules. A broad band at  $3303.409\text{ cm}^{-1}$  corresponds to O–H stretching from hydroxyl groups of water or phenolic compounds. The peak at  $1634.392\text{ cm}^{-1}$  indicates N–H bending or C=O stretching, suggesting biomolecules like proteins or flavonoids are involved in reduction and stabilization. The peak at  $1343.462\text{ cm}^{-1}$  is attributed to C–N or C–O vibrations of functional groups such as alcohols, ethers, or esters. A strong band at  $417.074\text{ cm}^{-1}$  represents Zn–O stretching, confirming the formation of ZnO nanoparticles<sup>[12]</sup>

Figure 2.FTIR analysis of ZnO



### 3.3.SEM analysis

The SEM images of ZnO nanoparticles synthesized using Terminalia arjuna extract show important details about their surface morphology. The nanoparticles are mostly spherical to slightly irregular in shape, confirming successful green synthesis. Minor variations in shape occur due to biomolecules in the plant extract influencing particle growth. The particles show a fairly uniform distribution, though slight clustering is observed because of high surface energy and organic functional groups.<sup>[13]</sup> The nanoparticles exhibit a rough and somewhat porous surface, which increases the surface area. This larger surface area enhances applications such as antioxidant, antibacterial, photocatalytic, and sensing activities. The clustering and thin surface layer indicate the presence of organic molecules from the extract acting as stabilizing and capping agents. Overall, SEM analysis confirms the successful green synthesis and nanoscale formation of ZnO nanoparticles.<sup>[14]</sup>

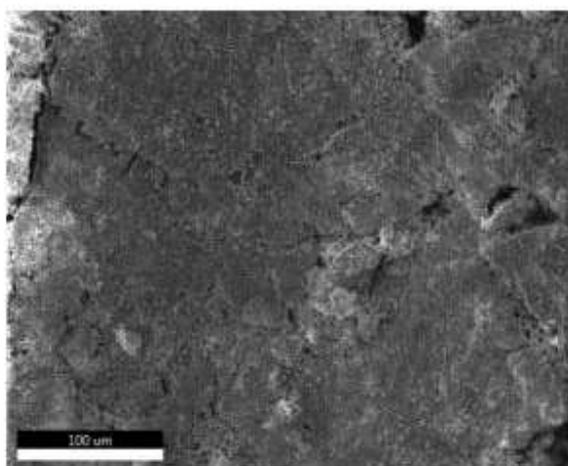
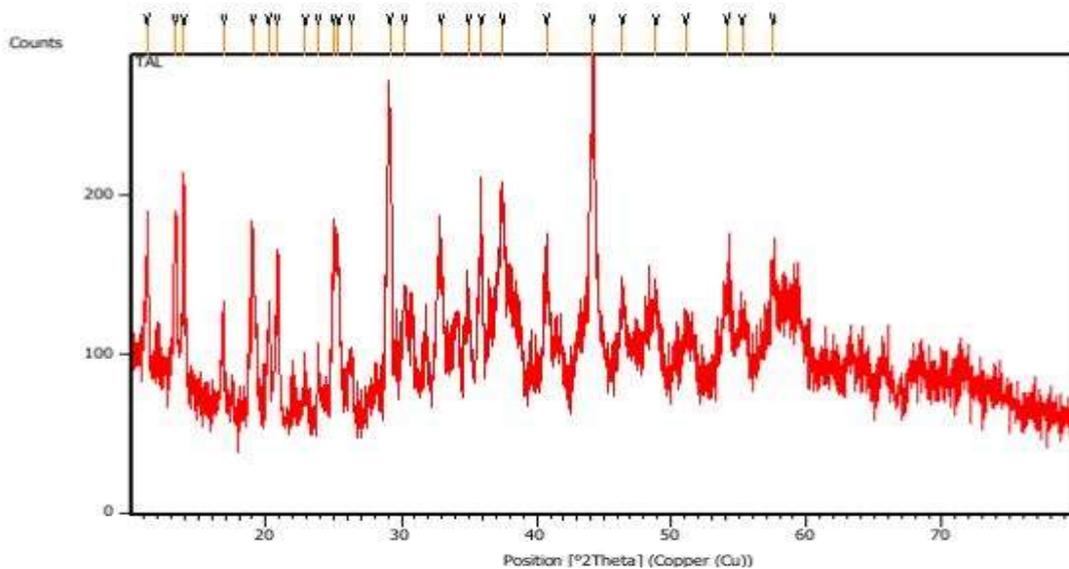


Figure 3.SEM Analysis of ZnO

### 3.4.XRD Analysis

The XRD analysis of ZnO nanoparticles confirms their crystalline nature. Diffraction peaks observed at  $31^{\circ}$ – $32^{\circ}$ ,  $34^{\circ}$ – $35^{\circ}$ ,  $36^{\circ}$ – $37^{\circ}$ ,  $44^{\circ}$ ,  $54^{\circ}$ – $56^{\circ}$ , and  $58^{\circ}$ – $63^{\circ}$  correspond to characteristic reflections of ZnO. These peaks are indexed to the crystal planes (100), (002), (101), (102), (110), (103), (200), (112), and (201) of the hexagonal wurtzite structure. The strong peak near  $44^{\circ}$ – $45^{\circ}$  corresponding to the (101) plane confirms the formation of ZnO nanoparticles. The absence

of additional impurity peaks indicates the high purity of the synthesized nanoparticles. The calculated FWHM values suggest nanoscale crystallite size, confirming nanocrystalline ZnO formation. The sharp and intense peaks with d-spacing values (7.88–1.78 Å) further support the well-structured crystalline phase.<sup>[15]</sup>



**Figure 4 XRD Pattern of ZnO**

## BIOLOGICAL ACTIVITY

### 3.5. Antioxidant Assay

The antioxidant activity of the synthesized Zn–TAL sample was evaluated using the DPPH free radical scavenging method. In this study, ascorbic acid was used as the standard antioxidant. The activity was measured by calculating the percentage of DPPH radical inhibition at different concentrations.<sup>[16]</sup> The results showed that ascorbic acid exhibited strong antioxidant activity, which increased with increasing concentration. The highest inhibition observed was 65.27% at 10 µg/ml, indicating effective free radical scavenging ability. The standard calibration graph showed good linearity. The regression coefficient value  $R^2 = 0.9871$  confirms the accuracy and reliability of the experimental results.<sup>[17]</sup>

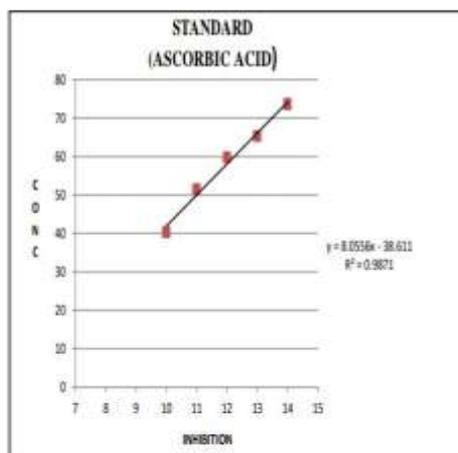


Figure 5. Graph of standard ascorbic acid

Concentration(µg/ml)	%Inhibition
10	40.27
11	51.38
12	59.72
13	65.27
14	73.61

Table 1. Standard Ascorbic acid

Concentration (µl)	%Inhibition
5	75
10	65.27
15	45.83
20	40.27
25	18.05

Table 2. % Inhibition of Zn-TAL

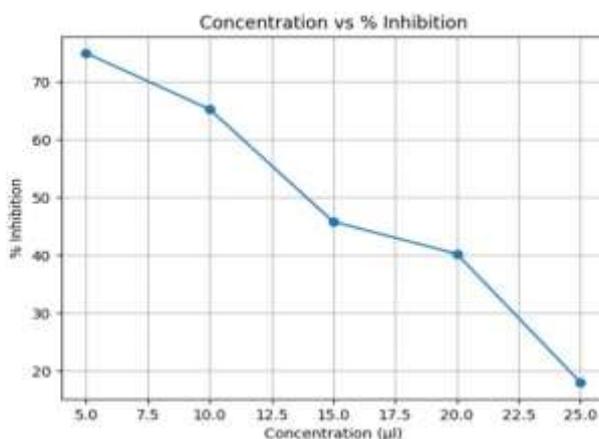


Figure 6. Graph of sample Zn-TAL

### 3.6. Antimicrobial Activity

The antibacterial and antifungal activities of the synthesized TAL–ZnO nanoparticles are presented in Table 4 and Figure 7. The antibacterial study showed a zone of inhibition of 17.3 mm against *S. aureus* and 20 mm against *E. coli*, indicating effective antibacterial activity. In the antifungal study, the nanoparticles showed 14.5 mm inhibition against *C. albicans* and 24.1 mm against *A. niger*. These results demonstrate that the biosynthesized ZnO nanoparticles possess significant antimicrobial properties. The observed activity is comparable to the standard positive control, confirming their potential effectiveness against microbial pathogens.<sup>[18]</sup>



Figure7: Antibacterial and Anti-fungal activities of synthesized ZnO nanoparticle

sample	Staphylococcus aureus	Escherichia Coli	Candidaaldicans	Aspergillus niger
Negative control(solvent)	-	-	-	-
Standard antibiotic (positive control)	20	27	15	31
TAL	17.3±0.57	20.6±0.57	14.5±0.50	24.5±0.45

**Table 3. Antimicrobial activity of synthesized ZnO nanoparticles**

#### 4. CONCLUSION

This study investigates ecofriendly synthesis of ZnO nanoparticles using extraction of leaves of Terminalia arjuna. The availability of phytochemicals in the plant extract provided d as reducing agent for reducing zinc to Zn nanoparticles without any additional hazardous chemicals. UV analysis revealed that peak at 232 nm indicates the presence of ZnO nanoparticle . FTIR study showed the strong peak observed the lower frequency of 417.074 cm-1 Represents the characteristic Zn-O stretching vibration, which definitively Confirms the formation of the ZnO nanoparticle structure. The SEM image shows that the ZnO nanoparticles are predominantly nearly spherical to irregular in shape. The antioxidant activity showed that 65% of inhibition at 5 µm. In XRD the d-spacing values, ranging from 7.88 Å to 1.78Å, which confirm that the green synthesis method using terminalia arjuna effectively produces crystalline ZnO nanoparticles with a well-defined hexagonal wurtzite structure. The synthesized nanoparticles showed remarkable antibacterial and anti fungal activities against pathogenic bacteria and fungal species and thus can be used to promising antimicrobial agents in future. The use of environmentally foreign material like plant extracts for the synthesis of nanoparticles offers numerous benefits of eco-friendly and compatibility.

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