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GREEN SYNTHESIS OF ZINC OXIDE NANOPARTICLES USING TULSI (OCIMUM SANCTUM) LEAF EXTRACT

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ABSTRACT

Green synthesis of nanoparticles has become a viable, affordable, and sustainable substitute for traditional physical and chemical synthesis methods. Ocimum sanctum (Tulsi), one of the many therapeutic plants, has drawn a lot of interest because of its remarkable phytochemical profile, biocompatibility, and stabilizing and educating properties. Without producing dangerous byproducts, tulsi-mediated synthesis produces nanoparticles with superior stability, antibacterial, antioxidant, anticancer, and anti-inflammatory qualities. The principles, process, characterization techniques, biomedical uses, and future prospects of green produced nanoparticles utilizing tulsi extract are highlighted in this paper.

Keywords: Tulsi, Green synthesis, Nanoparticles, Phytochemicals, Biomedical applications

Introduction

Nanotechnology has emerged as one of the most cutting-edge fields of modern research because to its remarkable advantages in pharmaceuticals, biology, electronics, food technology, and environmental sciences. The unique physicochemical properties of nanoparticles, which are typically between 1 and 100 nm in size, make them ideal for cutting- edge industrial and medical applications. These features include enhanced biological activity, optical behavior, high reactivity, and a huge surface-to-volume ratio.

Traditional nanoparticle synthesis techniques, like chemical and physical procedures, often include hazardous chemicals, high energy input, toxic solvents, and toxic byproducts. Due to these limitations, which have resulted in major environmental and health problems, the scientific community is being urged to transition to green and sustainable production techniques. Green nanotechnology uses biological resources such as plant extracts, enzymes, and natural polymers to create nanoparticles quickly, cheaply, and without harming the environment.Medicinal herbs have attracted a lot of interest among plant-mediated synthesis methods due to their inherent therapeutic value and rich phytochemical composition.

Ayurvedic and traditional Indian medical systems make substantial use of holy basil, also known as tulsi (Ocimum sanctum), a revered medicinal plant. Tulsi leaves include a variety of flavonoids, phenols, terpenoids, eugenol, rosmarinic acid, tannins, and essential oils that act as organic reducing, capping, and stabilizing agents when nanoparticles are being produced.

Tulsi leaf extract is a superior biogenic agent for a variety of biomedical and pharmaceutical applications since green synthesis utilizing it has been shown to produce nanoparticles with outstanding antibacterial, antioxidant, anti-inflammatory, anticancer, antiviral, and antifungal activities.

The procedure also shortens the production time, enhances the biocompatibility of nanoparticles, and does away with the requirement for harsh chemicals, providing a viable route toward environmentally friendly nanotechnology. The phytochemical properties of Tulsi, the processes involved in the formation of nanoparticles, synthesis techniques, characterization methods (UV-Vis, FTIR, XRD, SEM, TEM), and applications of Tulsi-mediated nanoparticles in agriculture, medicine, and environmental cleanup are all covered in detail in this review.

It delves deeper into challenges and potential directions for future research to improve the production of plant-assisted nanomaterials. Tulsi green synthesis creates a bridge between traditional herbal science and modern nanotechnology, promoting safer and more sustainable breakthroughs for upcoming industrial and medicinal advancements. Nanotechnology is an advanced branch of science that focuses on materials with sizes between one and one hundred nanometers. Traditionally, physical and chemical methods that use a lot of energy and dangerous materials were used to create nanoparticles.

Green synthesis using medicinal herbs offers a secure alternative. For thousands of years, Ayurveda has made considerable use of the sacred medicinal plant tulsi. Phytochemicals found in its foliage, including as flavonoids, phenols, terpenoids, tannins, and essential oils, serve as organic reducing, capping, and stabilizing agents for nanoparticle synthesis. Green synthesis with Tulsi Zinc oxide is an inorganic substance that is utilized in several production processes. Rubbers, plastics, ceramics, glass, cement, lubricants, paints, ointments, adhesives, sealants, pigments, edibles, batteries, ferrites, fire retardants, and first-aid tapes are among the materials that contain it. The majority of zinc oxide is created artificially, however it can be found naturally as the mineral zincates [8,9]. Numerous researchers have reported on the manufacture of ZnO nanoparticles for use in biological sciences and solar cell applications.

This feature made them suitable for use as antimicrobial agents, toxic to microbes, and biocompatible with human cells. Many common chemical techniques, including chemical precipitation, sonochemical, solvothermal, sol-gel process, hydrothermal decomposition, and others, can be employed to synthesize nanoparticles. Because of its ease of use, environmental friendliness, and broad antibacterial activity, the biological technique of producing ZnO nanoparticles is becoming more and more significant [3,10]. When heated, zinc acetate dehydrate, a crystalline zinc source that is somewhat soluble in water, breaks down into zinc oxide. It is easily accessible in the majority of quantities, including large amounts. Because of its many therapeutic qualities, Ocimum sanctum L. (also called Ocimum tenuiflorum, Tulsi) has been utilized as medicine for over thousands of years in Ayurveda, Indian traditional medicine, and related verbalism disciplines.

The taxonomical synonym O. sanctum L. is more common in Indian scientific literature since the plant is revered and worshipped in a sanctorum of its own in traditional Hindu temples, holy gardens, and homes throughout the subcontinent . Stress is reduced, and digestion and immunity are enhanced. Linalool, alkaloids, ursolic acid, glycosides, carvacrol, tannins, rosmarinic acid, and aromatic compounds are the chemical components of Ocimum tenuiflorum]. Green synthesis is used in this study to create zinc oxide nanoparticles.

Zinc oxide has a broad band gap, a high piezoelectric property, a significant binding energy, and many other remarkable characteristics. Numerous applications, including laser devices, optoelectronic devices, electromagnetic linked sensors, and surface acoustic wave devices, employ it . Since bulk zinc oxide cannot remove arsenic due to its large surface area, zinc oxide nanoparticles have been employed to remove sulfur and arsenic from water.

Zinc oxide has incredible uses in microelectronics, biomolecular detection, and diagnostics . According to published research, ZnO nanoparticles are produced using traditional techniques such as chemical reduction , laser ablation , solvothermal , inert gas condensation , and the sol-gel method. In contrast to the green synthesis process, this method requires high pressure, laser radiation, toxic chemicals, and inert gases like helium ac. Some of these traditional techniques are costly, difficult to use, need excessive attention during the process, and call for a certain kind of vessel, such as a polypropylene tank for the synthesis of nanoparticles. Recently, the Ocimum Tenuiflorum plant's leaf extract was used to create green ZnO nanoparticles. Other names for Ocimum Tenuiflorum include holy basil, tulsi, and Ocimum sanctum. It is a member of the Lamiacece family. Ocimum Tenuiflorum is primarily found in tropical areas. Linalool, alkaloids, ursolic acid, glycosides, carvacrol, tannins, rosmarinic acid, and aromatic compounds are among Ocimum Tenuiflorum's chemical components. Copper, gold, and silver nanoparticles have recently been synthesized using leaf extract from the Ocimum Tenuiflorum plant , . To the best of our knowledge, the green production of ZnO nanoparticles using leaf extract from the Ocimum Tenuiflorum plant has not been disclosed. Therefore, the current job involved synthesizing and characterizing ZnO nanoparticles utilizing an extract from the leaves of the Ocimum Tenuiflorum plant.

The aim of the creative and new field of nanotechnology is to create unique materials at the nanoscale Scale. Nanomaterials, which are made up of tiny particles with a high specific surface area as compared To materials with specified particle sizes, provide materials with unanticipated surface area, volume, Atomic size, and macro tunnelling effects. Nanomaterials have a wide range of possible applications Because of the distinctive optical, mechanical, catalytic, and biological qualities theyex

Due to Their large specific surface area, bio – compatibility, uv light scattering and absorption, and Antimicrobial capabilities, ZnO NPs are a type of nanomaterial that is usually employed in the field of Electrochemistry, medical instruments, cosmetology, and textile industry, etc. Physical and Chemical processes are usually used to produce ZnO NPs, with the latter having the drawbacks of high Energy requirements, low accuracy, irregular size .

The Primary Aim

Using the bio-reductants found in Tulsi leaf extract, a sustainable, economical, and non-toxic “green” approach for the synthesis of zinc oxide nanoparticles will be developed, and the physical and chemical characteristics of the final nanoparticles will be assessed.

Specific Objectives

The study concentrates on these crucial technical benchmarks in order to accomplish the Phyto-Reduction: This process uses Ocimum sanctum’s secondary metabolites, such as flavonoids, alkaloids, and polyphenols, to convert zinc precursors, such as zinc nitrate or zinc acetate, into nanoscale zinc oxide. • Optimization: To control the size and form of the nanoparticles by identifying the optimal reaction conditions, particularly pH, temperature, concentration, and incubation time. • Characterization: To verify the ZnO NPs’ production and examine their morphology using conventional analytical methods:

- UV-Vis Spectroscopy: To verify the peak of surface plasmon resonance (SPR).
- FTIR: To determine which functional groups

are in charge of stabilization and capping.

- XRD: To ascertain the grain size and crystalline To prepare zinc oxide nanoparticles (ZnO NPs) using Tulsi leaf extract by green synthesis method.

To utilize Tulsi leaf phytochemicals as natural reducing and stabilizing agents for eco- friendly nanoparticle synthesis. To optimize the synthesis conditions such as pH, temperature, concentration, and reaction time for formation of ZnO nanoparticles.

To characterize the synthesized ZnO nanoparticles using analytical techniques such as: Uv Visible Spectroscopy X-Ray Diffraction (XRD) Fourier Transform Infrared Spectroscopy (FTIR) Scanning Electron Microscopy (SEM)

To evaluate the antibacterial activity of ZnO nanoparticles against selected microorganisms. To study the antioxidant activity of Tulsi-mediated ZnO nanoparticles. To compare green synthesized ZnO nanoparticles with chemically synthesized nanoparticles.

To develop a simple, cost-effective, and environmentally safe method for nanoparticle production.To explore the pharmaceutical and biomedical applications of green synthesized ZnO nanoparticle.

Role of Tulsi Extract

In green synthesis, the Ocimum sanctum extract serves two critical functions that replace chemicals used in industry: • As a Reducing Agent: Flavonoids, polyphenols, and terpenes, particularly eugenol, are abundant in tulsi leaves. These compounds donate electrons to the Zinc ions (Zn^{2+}), converting them into metallic zinc or zinc complexes. • As a Capping/Stabilizing Agent: The proteins and long-chain carbohydrates in the extract encircle the nanoparticles once they develop. This keeps the particles at the nanoscale by preventing them from "clumping" together (agglomeration).

Tulsi leaf extract plays an important role in the green synthesis of zinc oxide nanoparticles (ZnO NPs). The extract contains various phytochemicals such as flavonoids, phenols, tannins, terpenoids, eugenol, and alkaloids which help in nanoparticle formation.

Main Roles of Tulsi Extract

1. Reducing Agent

Tulsi extract converts zinc ions (Zn^{2+}) from zinc salts like zinc sulfate or zinc nitrate into zinc oxide nanoparticles. The phytochemicals donate electrons and reduce metal ions during the reaction.

2. Stabilizing Agent

Tulsi phytochemicals surround the nanoparticles and prevent aggregation (clumping). This helps maintain:Stability Small particle size Uniform distribution

3. Capping Agent

Bioactive compounds present in Tulsi form a protective coating on nanoparticles. This coating improves: Shelf life Surface stability Biological activity

4. Eco-Friendly Synthesis

Tulsi extract replaces harmful chemical reducing agents. Therefore, the synthesis becomes: Non-toxic Environmentally safe Cost-effective Control of Particle Size and Shape

The concentration of Tulsi extract influences:

Size of nanoparticles hape and morphology Crystallinity

Higher phytochemical concentration may produce smaller and more stable nanoparticles.

5. Enhancement of Biological Activity

Tulsi contains medicinal compounds with antimicrobial and antioxidant properties. These compounds may enhance:

Antibacterial activityAntioxidant activity

Anti-inflammatory effect of ZnO nanoparticles

Application Testing (Optional but Common): To Examine the produced nanoparticles' biological potential, including any antibacterial, antioxidant, or photocatalytic properties.

6. Improvement of Antioxidant Properties

Natural antioxidants present in Tulsi improve free radical scavenging activity of ZnO nanoparticles.

7. Biocompatibility Enhancement

Tulsi-mediated nanoparticles are considered more biocompatible and safer for biomedical applications coTmpared to chemically synthesized nanoparticles.

Fig no.1: Tulsi

Why tulsi

Tulsi is often referred to as the "Queen of Herbs" in this context because it is rich in Eugenol and Ascorbic acid. These compounds are highly efficient at donating electrons to Zinc ions, transforming them into stable nanoparticles without requiring high pressure or hazardous solvents. In this regard, tulsi is frequently referred to as the "Queen of Herbs" due to its high eugenol and ascorbic acid content. These substances donate electrons to zinc ions very effectively, turning them into stable nanoparticles without the need for dangerous solvents or high pressure.

Key Reaction Insight: In simple terms, the process follows this path: Zinc Precursor + Tulsi Extract → Stirring/Heating → Zinc Hydroxide Complex → Calcination → ZnO .. .

The Mechanism of Synthesis.

The transformation happens in three distinct phases:

Phase A: Activation (Reduction)

The polyphenolic chemicals react with the zinc ions when the extract is combined with the zinc precursor, such as zinc nitrate.

Phase B: Nucleation

Reduced zinc atoms start to group together as their concentration rises. The nanoparticle's "birth" occurs here. Here, the pH of the solution is crucial; higher pH values typically hasten this process.

Phase C: Growth and Stabilization

The clusters develop into bigger particles. The Tulsi extract's biomolecules adhere to these

particles' surfaces. In order to eliminate biological debris and leave behind pure, crystalline ZnO, the mixture is often dried and calcined (heated to high temperatures, such as 400°C).

ZnO Nanostructure Types Produced

Different "shapes" or types of nanoparticles may arise depending on the pH, temperature, and concentration utilized during the Tulsi-mediated synthesis. These forms alter the way particles function in electronics or medicine:

Type/Morphology description use

Types/ morphology	Description	Common use
Spherical	The most common type of small uniform dots	Drug delivery and antibacterial
Nano flower	Cluster that look like petal high surface area	Photocatylasis (cleaning water)
Nanorods	Elongated cylinder like structure	Sensore and solar cells
Hexagonal	Well defined sid sided crystalline structure	Uv protection in sunscreen

Table no.1

Methodology.

Preparation of Tulsi Leaf Extract; Preparation of Tulsi Leaf Extract

Gather fresh tulsi leaves and give them a good wash in distilled water.After air drying, cut into tiny pieces. Add 100 milliliters of distilled water to 10 grams of tulsi leaves.For one to two hours, heat the tulsi leaf and water mixture at 60 to 80 degrees Celsius. The mixture should be cooled after heating before being filtered through Whatmann filter paper. Your plant extract (reducing and stabilizing ingredient) is called filtrate.The filtrate is kept in a refrigerator at 4 degreesCelsius.

Fig no.2 ocimum santctum [tulsi]leaf exract

Preparation of zinc sulphate solultion:
To make a 0.1 m zinc sulfate solution, dissolve 2.87 g of zinc sulfate.[anhydrous form] in 100 milliliters of distilled water.

Zinc oxide nanoparticle synthesis
Fill a beaker with 90 milliliters of $ZnSO_4$ solution. Add 10 ml of tulsi extract. Keep the temperature between 60 and 70°C.For one to two hours, stir constantly.

After heating, the solution's zinc sulphate and tulsi extract ph are obtained 9.69.the ph should be 9-12

Fig no 3. ph of the zinc oxide and Tulsi leaf extract

Next, centrifuge the mixture for 15 to 30 minutes at 8000 to 10000 rpm. Following centrifugation, the liquid supernant was extracted from the tube and cleaned with either ethanol or distilled water.

Fig no.4 centrifugation of zinc oxide nanoparticles

Observations:
The effective production of zinc oxide nanoparticles is typically indicated by a color shift from pale to milky white or brown. Or black colour

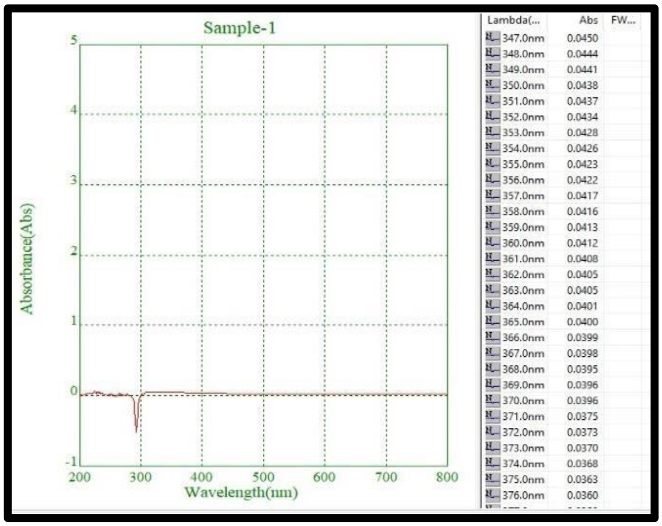
After that, the mixture was dried at 59 to 60 degrees in a hot air oven.Sonicate the sample for 15 to 30 minutes using distilled water or ethanol after it has dried. to carry out the UV anylisis after sonication.

Characterization Technique

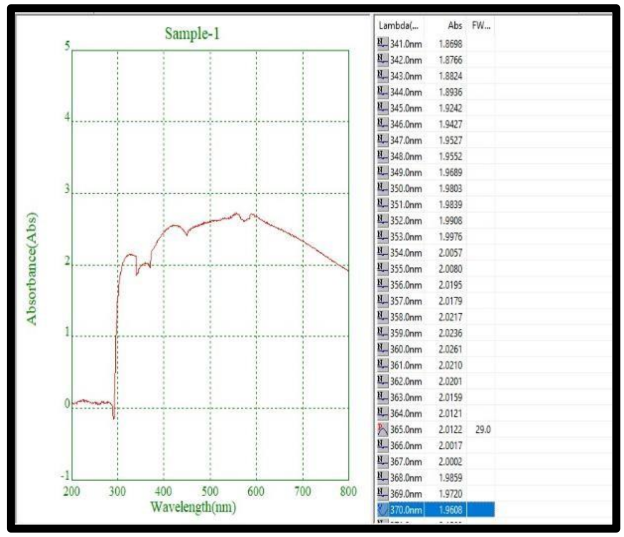
1) **UV-Visible Spectroscopy**

This is usually the first step to confirm the formation of nanoparticles. ZnO NPs exhibit a unique phenomenon called **Surface Plasmon Resonance (SPR)**.

- **Purpose:** To confirm the reduction of Zinc ions to ZnO.
- **Result:** A characteristic absorption peak (lambda max) is typically observed in the range of **300 nm to 370 nm**



Sample 1



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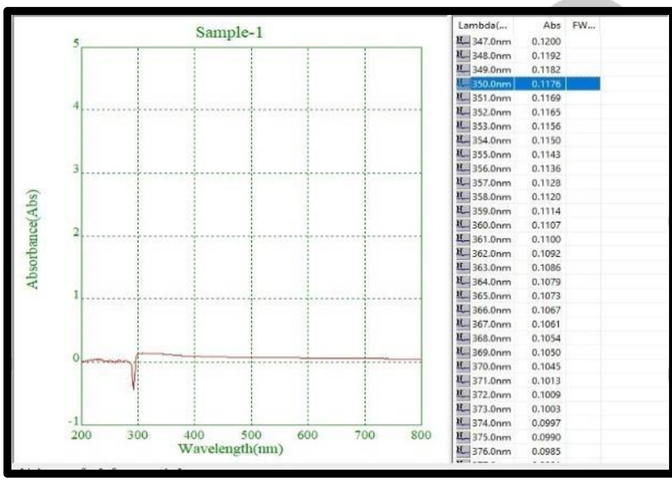

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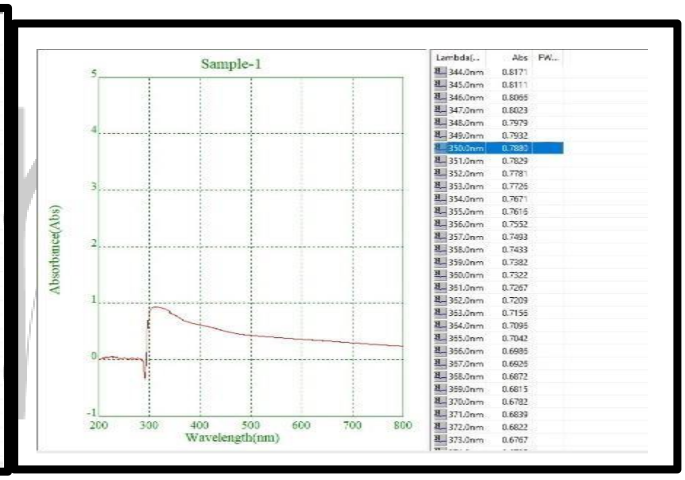

Sample 4

2) X-Ray Diffraction (XRD)

1. The crystalline structure and phase purity of the ZnO NPs are ascertained by XR• Goal: To determine the average grain size and locate the crystal lattice.$D = \frac{K\lambda}{\beta \cos \theta}$ (where D is the crystallite size, λ is the X-ray wavelength, θ is the Bragg angle, and β is the Full Width at Half Maximum).
2. FTIR, or Fourier Transform Infrared Spectroscopy
FTIR is essential to determine which biological molecules are in charge of the synthesis because you are employing Tulsi extract.
Goal: To determine which functional groups from the Tulsi extract are attached to the surface of the nanoparticles, such as hydroxyl, carbonyl, or amine groups.
3. High-resolution pictures of the nanoparticles' surfaces can be obtained using scanning electron microscopy (SEM) and EDX. • Goal: To examine the surface clusters and morphology (shape). • Energy Dispersive X-ray, or EDX, is frequently connected to the SEM and verifies the elemental _

3) Transmission Electron Microscopy (TEM)

TEM offers a significantly better resolution to view the inside structure, whereas SEM just displays the surface. • Goal: To ascertain the nanoparticles' precise size distribution and shape (such as spherical, rod-like, or hexagonal).

4) Analysis of Zeta Potential

For every application involving nanoparticles, stability is essential. • Goal: To gauge the nanoparticles' surface charge in a colloidal solution.

Summary Table of Techniques

Technique	**Information Provided**
UV-Vis	Initial confirmation & Bandgap energy
XRD	Crystallinity & Phase (Wurtzite)
FTIR	Capping agents (Tulsi phytochemicals)
SEM/TEM	Size and Shape (Morphology)
EDX	Elemental purity

Zeta Potential	Colloidal stability

Table no.2

1. **Biomedical Applications**

This is the most prominent field for Tulsi-derived ZnO NPs due to their high biocompatibility and low toxicity.

- Antimicrobial Agent: They function as "smart weapons" against fungi and bacteria that are resistant to multiple drugs, such as S. aureus and E. coli. Their use in creating antibacterial soaps and wound-healing lotions is highlighted by research conducted in 2024–2025.
- Anticancer Activity: ZnO NPs are comparatively harmless for healthy cells but have intrinsic cytotoxicity against cancer cells. Particularly in tumor cells, they cause oxidative stress (ROS), which results in apoptosis (cell death).
- Antioxidant Activity: Tulsi's phytochemicals, or capping agents, enable these nanoparticles to scavenge free radicals, which is beneficial for anti-inflammatory and anti-aging therapies.
- Drug Delivery: They can serve as carriers for targeted drug delivery, especially for insoluble pharmaceuticals, thanks to their high surface-area-to-volume ratio.

2. **Environmental Applications**

ZnO is a well-known semiconductor, making it an excellent candidate for "cleaning" the environment.

- Photocatalysis: These nanoparticles can break down harmful organic dyes from industrial textile wastewater, such as Methylene Blue or Congo Red, into innocuous compounds when exposed to UV or solar light.
- Water Purification: Bulk ZnO is ineffective at removing heavy metals like sulfur and arsenic from water sources. Agricultural Applications

With the shift toward "Nano-Agriculture," Tulsi-synthesized ZnO NPs are being used to improve crop yields sustainably.

- **Nano-Pesticides & Fungicides:** They protect crops from fungal infections (e.g.,
Aspergillus niger) without the toxic runoff associated with chemical pesticides.
- **Zinc Fertilizers:** Zinc is a vital micronutrient for plants. Nano-ZnO provides a slow- release source of zinc, promoting better seed germination and plant growth.

3. **Industrial & Consumer Goods**

- **Cosmetics and Sunscreens:** Due to their ability to absorb UV radiation while remaining transparent on the skin, they are a staple in "mineral" sunscreens. Being green-synthesized makes them more appealing for "organic" cosmetic lines.
- **Food Packaging:** ZnO NPs are incorporated into plastic films to create **antimicrobial food packaging**, which extends the shelf life of perishable goods by preventing bacterial growth.
- **Sensors:** Because of their high surface sensitivity, they are used in gas sensors to detect pollutants like NO_2 or

NH_3 at very low concentrations.

Summary of Benefits

Application	Role of ZnO NPs	Advantage of Tulsi Synthesis
Healthcare	Antiseptic/Antibiotic	Non-toxic; synergistic medicinal effect.
Environment	Wastewater treatment	Solar-active; biodegradable process.
Textiles	Self-cleaning fabrics	UV protection + antibacterial properties.
Food Industry	Preservatives	Safe for human contact (Bio-safe).

Table no.3

Advantages

The move toward **Green Synthesis** using Tulsi isn't just about being "eco-friendly"—it provides technical and economic advantages that traditional chemical and physical methods (like sol-gel or chemical vapor deposition) simply cannot match.

1. **Safety and Biocompatibility**

The most significant advantage is the **elimination of toxic reagents**.

- Non-Toxic Byproducts: Traditional synthesis frequently employs hydrazine or sodium borohydride as reducing agents, both of which are harmful to the environment and human health. Water and plant sugars/phenols are used in green synthesis.
- Enhanced Bio-safety: When utilized in medical applications (such as drug delivery or wound healing), the nanoparticles are far less likely to produce an immunological reaction or toxicity since they are capped with natural Tulsi phytochemicals.

2. **Cost-Effectiveness**

Green synthesis is a "budget-friendly" science.

- **Minimal Infrastructure:** It does not require high-pressure chambers, expensive vacuum systems, or high-energy lasers.
- **Cheap Raw Materials:** Tulsi is widely available and inexpensive. The "waste" from the process is essentially biodegradable plant matter.
- **Energy Savings:** Most green synthesis reactions occur at **room temperature** or low heating (60°C–80°C), whereas chemical methods often require extreme temperatures.

3. **"Two-in-One" Functionality (Reduction & Stabilization)**

In chemical synthesis, you must add a "reducing agent" to create the particle and a separate "stabilizing agent" (capping agent) to stop it from clumping.

- **Natural Dual-Action:** Tulsi extract performs both roles simultaneously. The polyphenols reduce the Zinc ions, and the proteins/terpenoids wrap around the nanoparticle to prevent **agglomeration** (clumping).

Synergistic Effects: The medicinal properties of Tulsi (antifungal, anti-inflammatory) are often "carried" by the nanoparticle, making the final product more potent than chemically made ZnO.

4. **Scalability**

- **Ease of Production:** The process is straightforward: extract, mix, and stir. This makes it very easy to scale from a small laboratory beaker to large industrial vats without complex chemical monitoring.
- **High Yield:** Plant-based methods typically offer high conversion rates of metal ions into nanoparticles.
-

5. **Environmental "Handprint"**

- **Zero Toxic Runoff:** The "waste" water from this process doesn't contain harsh solvents that can contaminate groundwater.
- **Carbon Footprint:** Lower energy requirements directly translate to a lower carbon footprint for the manufacturing process.

Comparison at a Glance

Feature	**Chemical Synthesis**	**Tulsi (Green) Synthesis**
Reducing Agent	Harsh chemicals (Hydrazine)	Tulsi Phytochemicals
Capping Agent	Synthetic Polymers (PVP/PEG)	Natural proteins/flavonoids
Solvent	Organic solvents (Toluene/DMF)	Water (Aqueous)
Cost	High	Very Low
Biological Risk	High (residual toxins)	Negligible / Safe

Table no.4

Disadvantages

1. **Batch-to-Batch Inconsistency**

This is the biggest hurdle for industrial standardization.

- Variable Phytochemistry: The soil,

season, plant age, and geographic location all affect the concentration of active chemicals in tulsi, such as flavonoids or eugenol.

- Outcome: Even if you use the exact same procedure, nanoparticles made in May may change somewhat in size or shape from those made in December.

2. Limited Control Over Morphology

- Chemical techniques enable "surgical" precision in nanoparticle shape control (e.g., flawless cubes, wires, or spheres).
- Heterogeneity: Green synthesis frequently produces a polydisperse sample, which is a mixture of various sizes and shapes as opposed to a homogeneous collection.
- Complexity: It is challenging to pinpoint the precise molecule regulating the crystal's growth at any given time due to the plant extract's hundreds of distinct compounds.

3. Purity and Residual Organic Matter

- Capping Contamination: Although they offer stability, natural capping agents are considered "impurities." The organic layer from the Tulsi may obstruct electrical conductivity if your application calls for ultra-pure ZnO (such as in high-end electronics or semiconductors).

Difficult Purification: It can be a laborious operation needing several centrifugation and washing cycles to remove the extra plant matter without harming the nanoparticles or causing them to clump together.

4. Stability and Shelf Life

- Biological Degradation: The coating may be vulnerable to oxidation or microbial development over extended periods of time due to its organic composition (proteins, carbohydrates, and lipids).
- Agglomeration: When these natural coatings degrade over time, the nanoparticles may adhere to one another (agglomerate), losing their "nano" characteristics.

5. Scalability Challenges (Downstreaming)

The collection is difficult to scale, but the reaction is.

- Centrifugation Limits: High-speed centrifugation is frequently required to gather the powder. Compared to the chemical precipitation employed in factories, doing this for 1,000 liters of solution is far more costly and energy-intensive.
- Slow Reaction Time: Compared to chemical reduction, which can occur in a matter of seconds, biological reduction typically takes hours or days.

Summary Table:

Disadvantage	Impact	Why it happens
Reproducibility	Low	Natural variation in Tulsi plants.
Purity	Medium	Presence of organic "capping" layer.
Precision	Low	Hard to get 100% identical shapes.
Time	Medium	Biological processes are slower than chemical ones.

Table no.5

Challenges And Future Perspective

The topic of green ZnO nanoparticle production utilizing tulsi extract is developing quickly. But getting from "lab-scale success" to "industrial-standard product" requires getting past a lot of technological obstacles.

Current Challenges

- Reproducibility and Standardization: Tulsi's phytochemical profile (eugenol, alkaloids, etc.) varies according to the plant's age, harvest season, and region. Because of this, it is challenging to create nanoparticles with the same characteristics in each batch.
- Morphology Control: Green synthesis frequently produces polydisperse samples, or a mixture of different sizes and forms, which can be difficult for high-tech electronics, whereas chemical approaches can precisely create "nano-rods" or "nano-flowers".
- Scale-up Obstacles: The downstream processing, particularly the centrifugation and filtration needed to isolate the nanoparticles from the leftover plant extract, is energy- intensive and challenging to handle on a metric-ton scale."
- Long-term Stability: The "capping" layer's natural biomolecules (proteins and sugars) make it vulnerable to biodegradation over time, which can result in the clumping (agglomeration) of nanoparticles and a loss of efficacy
- .Toxicity Data Gaps: Although "green" suggests safety, long-term ecotoxicological data on the interactions of these particular bio-capped particles with intricate ecosystems or human biological pathways over a number of years are currently lacking.

Future Perspective (2026 and Beyond)

This field's future is in the direction of "Precision Green Nanotechnology."

1. Integration of AI and Machine Learning
Researchers are using AI to predict how different Tulsi phytochemical concentrations would affect particle size. By making "digital twin" modeling possible before the actual synthesis, this raises the possibility of achieving the exact morphology needed.
2. Systems of Hybrid Synthesis
To improve the uniformity of the nanoparticles and speed up reaction times without sacrificing their "green" quality, green extract can be combined with mild physical triggers (such sonication or microwave-assisted synthesis).
3. Advanced Agricultural "Smart" Delivery generating biostimulatory ZnO NPs. In 2026, the focus has shifted from using these particles for feeding to using them as "nanocarriers" that unleash Tulsi's inherent antibacterial qualities only when a plant is stressed by a disease.
4. The Circular Bioeconomy
Because the entire lifespan of the plant is utilized, the environmental "handprint" is virtually eliminated when Tulsi "waste"—stems and leftover leaves from the essential oil industry—is used to make nanoparticles.
5. Regulation
StandardizationIt is expected that global standards for "Biogenic Nanomaterials" would progress significantly.
This would offer a certification process that would make it easier for green- synthesized ZnO to be approved for use in clinical medicine and commercial

Discussion

The formation of nanoparticles is confirmed by the specific absorption peak observed in the UV region.

- Verification of Synthesis: ZnO nanoparticles are characterized by a peak at 361 nm. The Surface Plasmon Resonance, which happens when the electrons on the nanoparticle's surface resonate with the incident light, is what causes this peak.

- Function of Tulsi Extract: Polyphenols and flavonoids, two phytochemicals found in Tulsi leaf extract, function as reducing agents to change zinc ions into metallic zinc and then as capping agents to stabilize the nanoparticles and stop agglomeration.
- Particle Size and Quality: The peak's sharpness suggests that the produced nanoparticles are monodispersed, or roughly uniform in size. The creation of tiny, high-quality ZnO nanoparticles is usually indicated by a peak in the 360–370 nm range.

Results

- The formation of zinc oxide nanoparticles synthesized using Tulsi leaf extract was confirmed by UV–Visible spectroscopy analysis in the wavelength range of 200–800 nm.
- The UV spectrum showed absorption peaks in the UV region around 300–370 nm, which indicates the formation of ZnO nanoparticles. ZnO nanoparticles generally exhibit characteristic absorption due to electronic excitation and surface plasmon resonance.
- Among the obtained spectra:
- One sample showed maximum absorbance around 350 nm with absorbance value approximately 0.78.

- Another sample exhibited absorbance near 365–370 nm with higher absorbance intensity. The formation of zinc oxide nanoparticles synthesized using Tulsi leaf extract was confirmed by UV–Visible spectroscopy analysis in the wavelength range of 200–800 nm.

Spectral Range: The distinctive Surface Plasmon Resonance (SPR) peak for zinc oxide nanoparticles is located in the highlighted area between 350 and 370 nm.

Conclusion

- The UV-visible spectroscopy analysis confirms the successful green synthesis of zinc oxide nanoparticles using tulsi leaf extract.
- The main peak at 361 nm with an absorbance of 2.256 provides an obvious "fingerprint" for the presence of these nanoparticles.
- By producing stable nanoparticles suitable for a variety of biotechnological and antimicrobial applications, this ecologically safe method effectively replaces chemical manufacturing.

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