IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 49, No. 3, June, 2025, pp. 281-290
Journal homepage: http://iieta.org/journals/acsm

Green Synthesis of Silver Nanoparticles Using Lemon Juice Extract and Low Laser Irradiation

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https://doi.org/10.18280/acsm.490307

Received: 1 March 2025
Revised: 8 April 2025
Accepted: 15 April 2025
Available online: 30 June 2025

Keywords:
silver nanoparticles, green synthesis, lemon juice extract, low laser irradiation, photothermal therapy

ABSTRACT

This study explores the eco-friendly synthesis of silver nanoparticles (Ag NPs) using lemon juice extract combined with low laser irradiation. The structural, optical, and morphological properties of the nanoparticles were characterized using X-ray diffraction (XRD), UV-visible spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and field emission scanning electron microscopy (FE-SEM). The results demonstrated high crystallinity and stability of Ag NPs, with XRD revealing a face-centered cubic (FCC) structure and strong diffraction peaks at $2\theta = 38.1°$, $44.3°$, and $64.4°$, corresponding to the 111, 200, and 220 planes, respectively. The crystallite size for Ag-L samples was calculated to be 37.22 nm, indicating well-defined nanocrystals. This method offers a sustainable approach to nanoparticle synthesis by eliminating the need for toxic chemical reducing agents and minimizing hazardous waste, thereby significantly reducing environmental impact compared to conventional chemical synthesis. The approach holds promise for applications in photothermal treatments and environmental remediation.

1. INTRODUCTION

Silver nanoparticles (Ag NPs) have gained substantial interest due to their remarkable optical, electrical, and antimicrobial properties, making them suitable for a wide range of applications, including medical devices, water treatment, and catalysis [1, 2]. The unique properties of Ag NPs, such as their high surface area-to-volume ratio and quantum effects, enable them to exhibit superior performance in various applications compared to their bulk counterparts [3]. Despite their promising applications, traditional chemical synthesis methods often involve hazardous chemicals, posing environmental and health risks [4]. Due to their size-dependent physicochemical properties, eco-friendliness, availability, and cost-effectiveness; green AgNPs have been used in a variety of biomedical applications, such as anti-bacterial, anti-fungal, anti-viral, anti-cancer, anti-inflammatory, and drug delivery agents [5]. Also used in AgNPs-incorporated membranes in water and wastewater treatment, and to propose potential solutions [6, 7].

The development of green synthesis methods for Ag NPs has become a focal point of research due to increasing concerns over environmental sustainability and safety [8]. Green synthesis methods utilize natural resources, such as plant extracts, bacteria, and fungi, which act as reducing and stabilizing agents, to produce nanoparticles in an eco-friendly manner [9]. These biological systems not only reduce the use of toxic chemicals but also enhance the biocompatibility of the synthesized nanoparticles, making them suitable for biomedical applications [10].

Lemon juice, rich in citric acid and other phytochemicals, has emerged as an effective reducing and stabilizing agent for nanoparticle synthesis [11]. Citric acid, a natural antioxidant found in lemon juice, facilitates the reduction of silver ions to metallic silver nanoparticles. Additionally, the presence of various organic compounds, such as flavonoids and polyphenols, aids in the stabilization of the synthesized nanoparticles, preventing their agglomeration [12]. This biogenic approach aligns with the principles of green chemistry, promoting the use of renewable resources and reducing environmental impact [13].

The advancements in nanotechnology have introduced the use of laser irradiation as a novel method to control the synthesis of nanoparticles. Laser irradiation offers precise control over the synthesis process, allowing for the fine-tuning of nanoparticle size, shape, and distribution by adjusting parameters such as laser power, wavelength, and irradiation time. This method also enables the synthesis of nanoparticles without the need for additional reducing agents, further simplifying the process and reducing potential environmental impact [14].

Combining lemon juice extract with low laser irradiation presents a promising approach for the green synthesis of Ag NPs. This study investigates the structural, optical, and morphological properties of Ag NPs synthesized using this combined method. The aim is to evaluate the feasibility of this approach and its potential applications in photothermal treatments and environmental remediation. By leveraging the natural reducing power of lemon juice and the precise control offered by laser irradiation, this method seeks to enhance the sustainability and efficiency of nanoparticle synthesis [15].

The use of lemon juice in nanoparticle synthesis has been previously explored, showing promising results in terms of nanoparticle stability and biocompatibility. For example, it has been demonstrated that lemon juice can effectively reduce silver ions to silver nanoparticles [10], with the resulting nanoparticles exhibiting significant antimicrobial activity. Furthermore, highlighted the role of citric acid in stabilizing silver nanoparticles, preventing their aggregation and ensuring their long-term stability [12].

Laser irradiation, on the other hand, has been employed to synthesize various types of nanoparticles, including gold and silver, by providing a non-thermal energy source that facilitates the reduction of metal ions in solution. This technique allows for the production of nanoparticles with controlled sizes and shapes, which are critical parameters for their application in areas such as drug delivery and photothermal therapy [16].

In this study, we combine these two green synthesis techniques to produce silver nanoparticles with enhanced properties. By utilizing lemon juice extract and low laser irradiation, we aim to create a synthesis method that is not only environmentally friendly but also efficient in producing high-quality nanoparticles suitable for a variety of applications. The characterization of these nanoparticles will provide insights into their structural, optical, and morphological properties, furthering our understanding of their potential uses in medical and environmental fields.

2. METHODOLOGY

2.1 Materials and reagents

For the synthesis of Ag NPs, analytical grade Silver Nitrate ($AgNO_3$) with 99.9% purity was used. Organic lemons were utilized to extract lemon juice, standardized for citric acid content. A continuous-wave diode laser system was employed for laser irradiation. Distilled water served as the solvent. Characterization was performed using a UV-Vis spectrophotometer, transmission electron microscope (TEM), dynamic light scattering (DLS) device, FTIR spectroscope, and zeta potential analyzer.

2.2 Synthesis of silver nanoparticles

A 0.01 M $AgNO_3$ solution was mixed with lemon juice extract in varying volumetric ratios (1:1, 1:2, 1:3 v/v) to explore the effect of different concentrations. The mixture was subjected to laser irradiation under controlled conditions, with power settings ranging from 10 mW to 100 mW and durations between 1 to 30 minutes. The synthesis process was monitored using in-situ UV-Vis spectroscopy to observe nanoparticle formation and progression.

2.3 Characterization techniques

The synthesized nanoparticles were extensively characterized to determine their properties and stability. TEM was used for morphological analysis, and DLS measured particle size and distribution. UV-Vis and photoluminescence spectroscopy provided insights into the optical properties. FTIR spectroscopy identified chemical bindings and functional groups involved in reduction and stabilization. Zeta potential measurements assessed colloidal stability.

2.4 Experimental setup

A detailed schematic representation of the experimental setup was created to illustrate the process from the preparation of the reaction mixture to the laser irradiation and subsequent characterization steps (Figure 1).

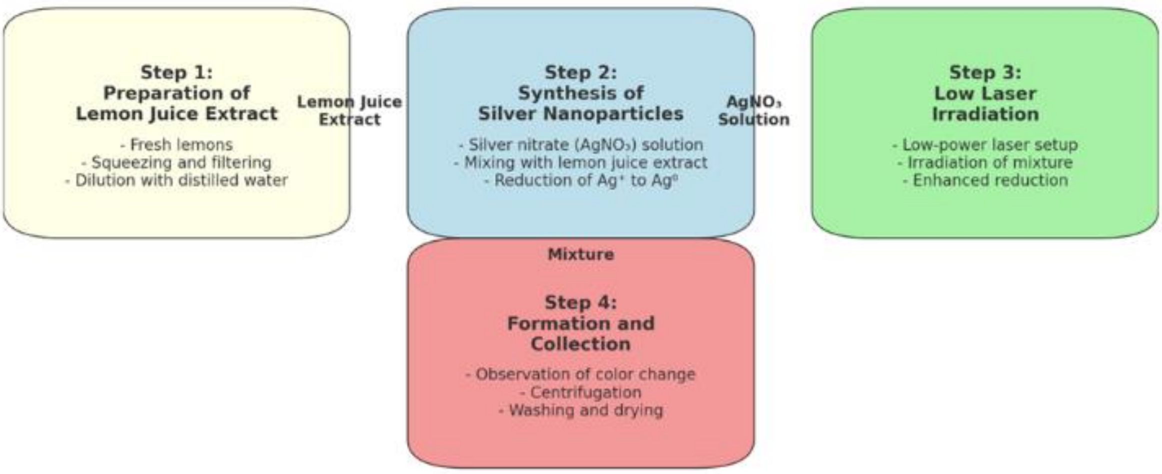


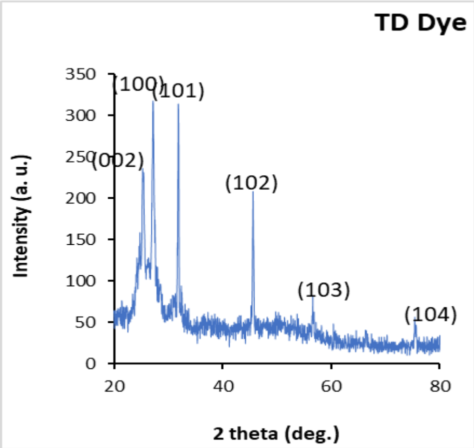
Figure 1. Schematic representation of the experimental process for the synthesis of silver nanoparticles using lemon juice extract and low laser irradiation

3. RESULTS AND DISCUSSION

3.1 Structural properties

XRD analysis

X-ray diffraction (XRD) patterns confirmed the crystalline structure of the synthesized Ag NPs, which exhibited a face-centered cubic (FCC) structure (Figure 2). The high-intensity peaks observed in the XRD patterns of Ag-TB and Ag-L samples indicate efficient reduction of $AgNO_3$ to metallic Ag (Table 1). This enhanced crystallinity aligns with the findings [15], who highlighted the role of phytochemicals in stabilizing nanoparticles.



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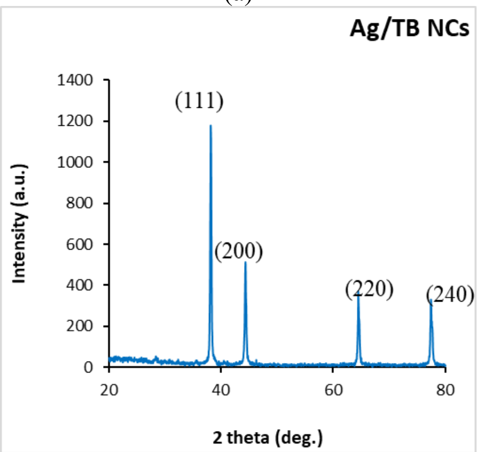

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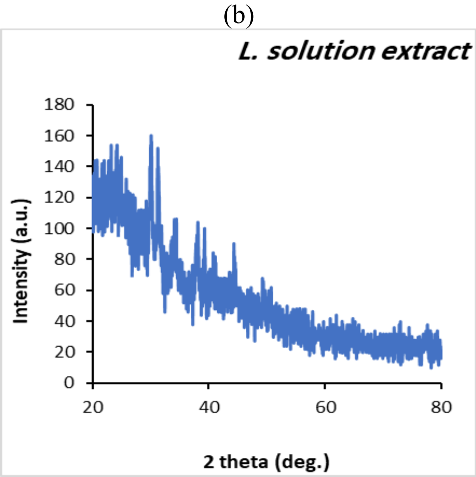

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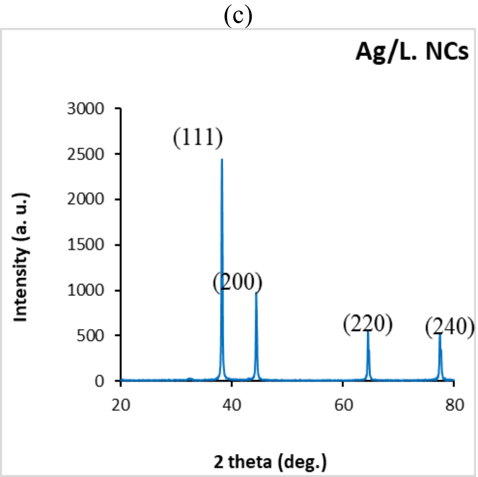

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Figure 2. XRD patterns of synthesized Ag NPs

Table 1. Crystallite size, dislocation density, and microstrain of samples

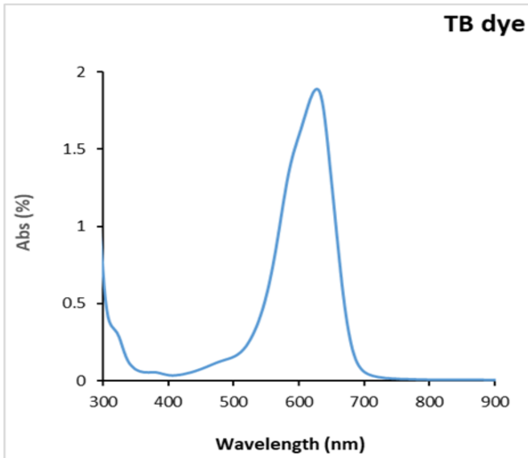
Sample	Crystallite Size (nm)	Dislocation Density (lines/m^2) ×1015	Microstrain ($\xi \times 10^{-3}$)
TB dye	13.98	51.16	24.78
Ag-TB	71.14	1.97	4.87
Lemons	29.16	11.75	11.88
Ag-L	37.22	7.21	9.31

3.2 Optical properties

UV-Visible spectroscopy

UV-Visible spectroscopy is a powerful tool for characterizing the optical properties of nanoparticles, particularly in identifying plasmon resonance bands that indicate successful nanoparticle formation. In this study, UV-Visible spectroscopy was employed to examine the synthesized silver nanoparticles (Ag NPs) using lemon juice extract (Ag-L) and those synthesized with Touilodin Blue Dye (Ag-TB) composites.

The UV-Visible absorption spectra revealed distinct plasmon resonance bands within the 400-500 nm range for the Ag-L nanoparticles (Figure 3). Plasmon resonance bands are indicative of the collective oscillation of free electrons in response to light, a hallmark of nanoparticle formation. The observed bands suggest that the Ag-L nanoparticles were successfully synthesized and that they exhibit the characteristic optical properties of silver nanoparticles. The specific range of 400-500 nm is consistent with the known plasmon resonance of silver nanoparticles, which typically appears around this region depending on particle size, shape, and surrounding medium.



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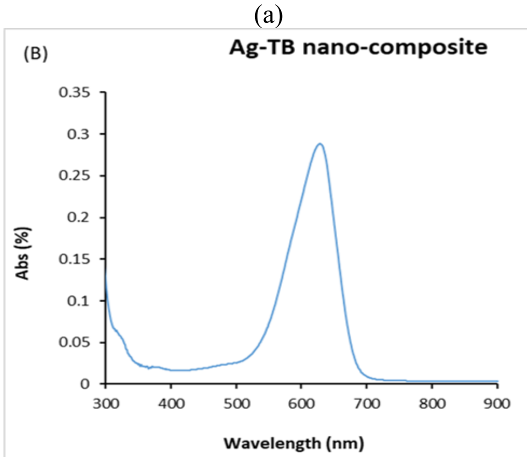

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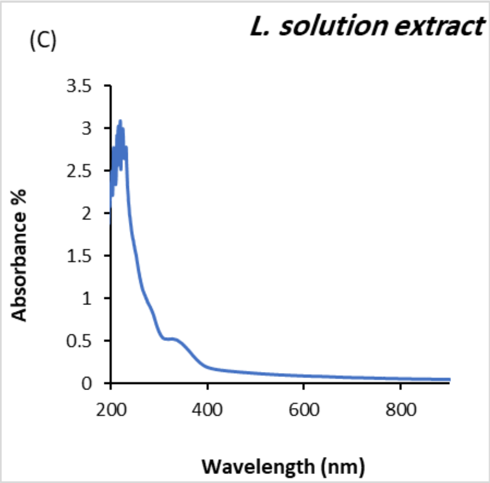

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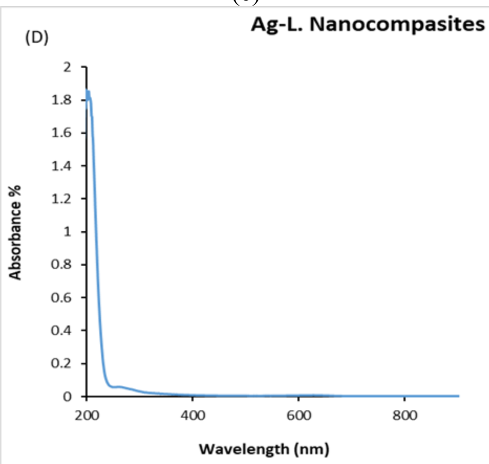

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Figure 3. UV-Visible absorbance spectra of synthesized Ag NPs

For the Ag-TB composite, the absorption spectrum exhibited a notable red shift compared to the Ag-L nanoparticles. A red shift in the absorption spectrum occurs when the peak wavelength of the plasmon resonance band moves towards the longer wavelength (red) end of the spectrum. This shift suggests an interaction between the Touilodin Blue Dye and the Ag NPs, which can alter the local refractive index around the nanoparticles and change their optical properties. The presence of the dye likely induces changes in the electron density distribution on the surface of the nanoparticles, leading to this shift.

This interaction between the dye and the nanoparticles can enhance the stability of the Ag NPs and modify their surface properties, making them more suitable for specific applications such as photothermal therapy, where precise control over the optical properties of nanoparticles is crucial. The red shift also indicates potential changes in the particle size and aggregation state, as larger or more aggregated particles typically exhibit resonance at longer wavelengths.

The UV-Visible spectra thus provide critical information about the successful synthesis and functional properties of the Ag NPs. The clear plasmon resonance bands confirm the presence of metallic silver in the nanoparticle form, while the shifts observed in the presence of the dye demonstrate the ability to tailor the optical properties through surface modification. These findings are aligned with previous studies that have utilized plant extracts and dyes in nanoparticle synthesis, highlighting the efficacy of green synthesis methods in producing stable and functional nanoparticles [17].

3.3 FTIR analysis

Fourier-transform infrared (FTIR) spectroscopy is an essential analytical technique used to identify the chemical bonds and functional groups present in a sample. In this study, FTIR spectroscopy was employed to analyze the chemical composition of the synthesized silver nanoparticles (Ag NPs) using lemon juice extract (Ag-L) and the Touilodin Blue Dye (Ag-TB) composites.

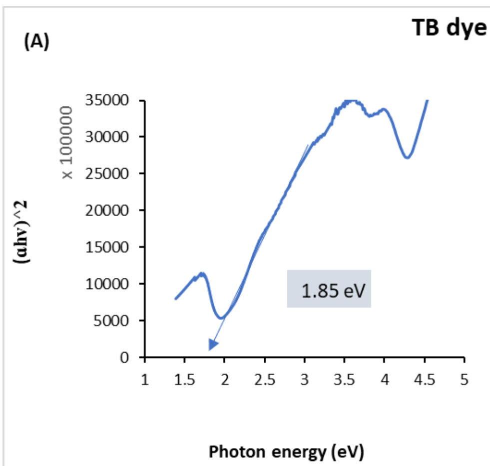
The FTIR spectra revealed several characteristic peaks corresponding to functional groups involved in the reduction and stabilization of the Ag NPs (Figure 4). Notably, peaks associated with -NH (amine), -CO (carbonyl), and -OH (hydroxyl) groups were identified. These functional groups play critical roles in the synthesis and stabilization processes of nanoparticles.

The presence of -NH groups is typically indicated by absorption bands around 3200-3500 cm^{-1}, corresponding to N-H stretching vibrations. These groups can originate from amino acids, proteins, or other nitrogen-containing compounds present in the lemon juice extract or dye. The amine groups are known to bind strongly to the nanoparticle surface, providing stability and preventing aggregation.

The carbonyl groups (-CO) were identified by strong absorption bands around 1650-1750 cm^{-1}, corresponding to C=O stretching vibrations. Carbonyl groups can come from organic acids, flavonoids, and other phytochemicals in the lemon juice extract. These groups are crucial for the reduction of silver ions (Ag^{+}) to metallic silver (Ag^{0}), facilitating the formation of nanoparticles.

Hydroxyl groups (-OH) were indicated by broad absorption bands around 3200-3600 cm^{-1}, corresponding to O-H stretching vibrations. These groups, abundant in citric acid and other polyphenolic compounds in lemon juice, also contribute to the reduction process and further stabilize the nanoparticles by forming hydrogen bonds with water molecules in the colloidal solution.

The identification of these functional groups supports the role of lemon juice extract and Touilodin Blue Dye as effective reducing and stabilizing agents in the green synthesis of Ag NPs. The FTIR spectra provide clear evidence of the chemical interactions occurring during the synthesis process, highlighting how the phytochemicals in lemon juice and dye interact with silver ions.



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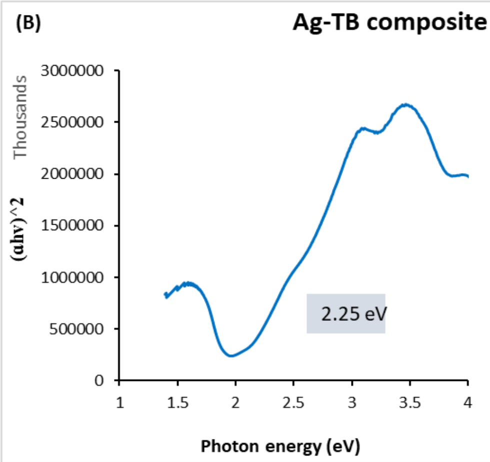

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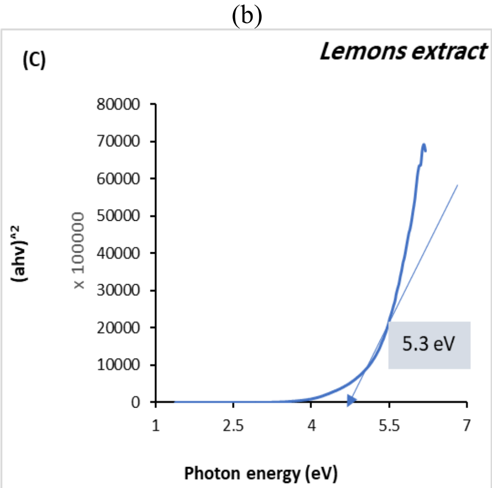

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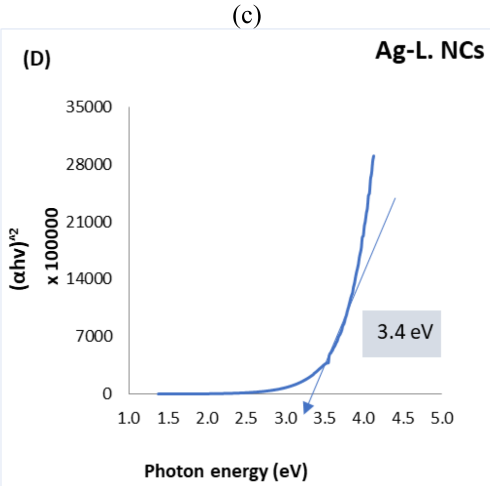

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Figure 4. FTIR spectra of synthesized Ag NPs

These findings are consistent with the work [18], who demonstrated similar chemical interactions in the synthesis of nanoparticles using plant extracts. Their study also identified the involvement of -NH, -CO, and -OH groups in the reduction and stabilization processes, underscoring the importance of these functional groups in the green synthesis of nanoparticles.

The FTIR analysis confirms that the use of lemon juice extract and Touilodin Blue Dye not only facilitates the reduction of silver ions but also imparts stability to the nanoparticles through the formation of strong chemical bonds. This green synthesis method thus offers a sustainable and environmentally friendly approach to producing stable and functional silver nanoparticles.

3.4 Morphological analysis

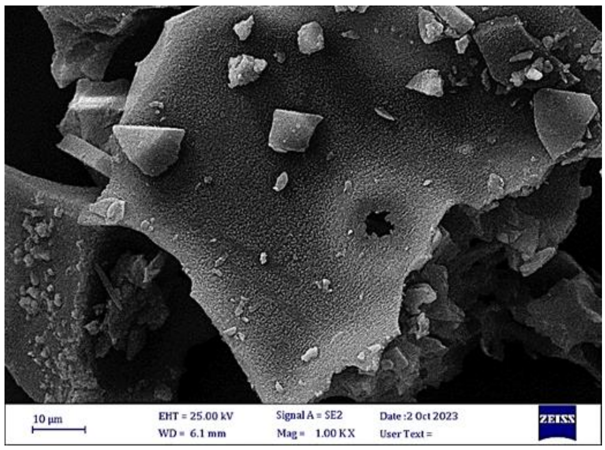
FE-SEM imaging

Field Emission Scanning Electron Microscopy (FE-SEM) was employed to analyze the morphology and size distribution of the synthesized silver nanoparticles (Ag NPs). The FE-SEM images revealed that the nanoparticles were uniformly distributed and exhibited a semi-spherical shape, with sizes ranging from 20-40 nm (Figure 5).

The uniformity in size and shape of the Ag NPs is particularly significant for their potential applications. In photothermal therapy, for instance, the size and shape of nanoparticles can influence their ability to convert light into heat efficiently. Uniform nanoparticles ensure consistent absorption and scattering of light, leading to effective and targeted heating of cancer cells without damaging surrounding healthy tissues. This precision in targeting is crucial for the success of photothermal therapy.

Similarly, in environmental remediation, the uniformity of nanoparticles enhances their reactivity and interaction with contaminants. The consistent size and shape of the Ag NPs facilitate uniform distribution and contact with pollutants, improving their efficacy in degrading harmful substances in water and soil. Additionally, the semi-spherical shape of the nanoparticles provides a larger surface area for interaction, further boosting their reactivity and efficiency in remediation processes.

These findings align with the work [13], who emphasized the importance of nanoparticle uniformity in determining their functional properties. Their research demonstrated that nanoparticles with uniform size and shape exhibit enhanced stability and reactivity, making them more suitable for various applications, including medical therapies and environmental cleanup efforts.



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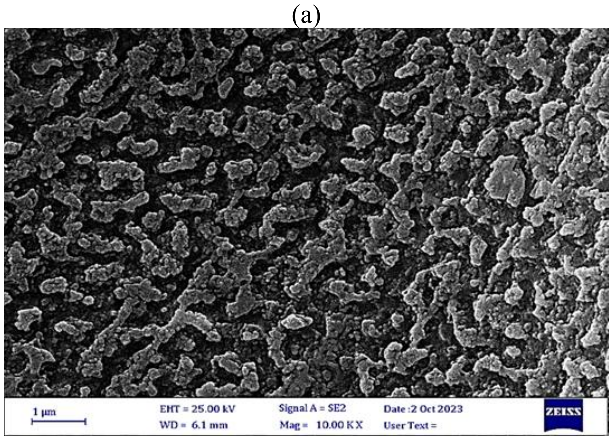

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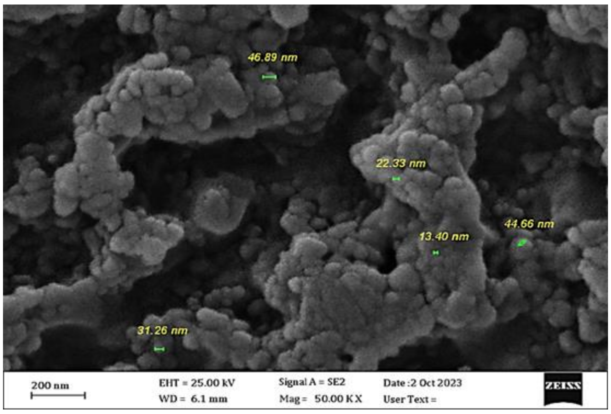

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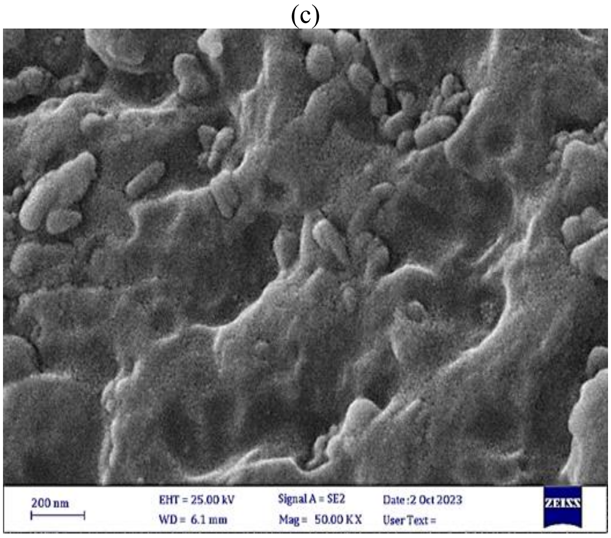

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Figure 5. FE-SEM images of synthesized nanoparticles

The FE-SEM analysis in this study confirms that the green synthesis method using lemon juice extract and low laser irradiation produces highly uniform and stable Ag NPs. This uniformity not only enhances the functional properties of the nanoparticles but also underscores the effectiveness of the synthesis method in producing high-quality nanomaterials suitable for advanced applications in photothermal therapy and environmental remediation.

3.5 TEM analysis

Transmission Electron Microscopy (TEM) was utilized to further confirm the morphology and size distribution of the synthesized silver nanoparticles (Ag NPs). TEM analysis provided high-resolution images that revealed detailed structural information, corroborating the findings obtained from FE-SEM. The TEM images (Figure 6) demonstrated that the Ag NPs synthesized using lemon juice extract and low laser irradiation were spherical in shape and exhibited a uniform size distribution, with diameters ranging between 20-40 nm. This consistent size and shape distribution is indicative of a controlled synthesis process, which is essential for applications that demand precision.

Uniform nanoparticles can be functionalized with targeting ligands to selectively bind to specific cells or tissues. Consistent size ensures predictable pharmacokinetics and biodistribution, enhancing the efficacy and safety of drug delivery systems. Additionally, the uniform size of nanoparticles allows for more predictable drug loading and release profiles, which is crucial for maintaining therapeutic drug levels over extended periods, reducing the frequency of administration, and improving patient compliance.

In photothermal therapy, uniformly sized nanoparticles exhibit consistent optical properties, such as plasmon resonance, which is vital for converting absorbed light into heat efficiently. This property is leveraged in photothermal therapy to selectively destroy cancer cells by heating them without affecting surrounding healthy tissues. The use of uniform nanoparticles reduces the risk of non-specific heating, which can cause damage to healthy cells and tissues. This precision in targeting ensures that only the diseased cells are affected, thereby minimizing side effects.

The results of this study align with the findings of several other researchers who have highlighted the importance of nanoparticle uniformity in various applications. For instance, Song and Kim [9] emphasized that nanoparticles with uniform size and shape exhibit enhanced stability and reactivity, making them more suitable for medical and environmental applications. Similarly, Kaviya et al. [10] reported that biologically synthesized nanoparticles often exhibit superior uniformity compared to those synthesized using traditional chemical methods.

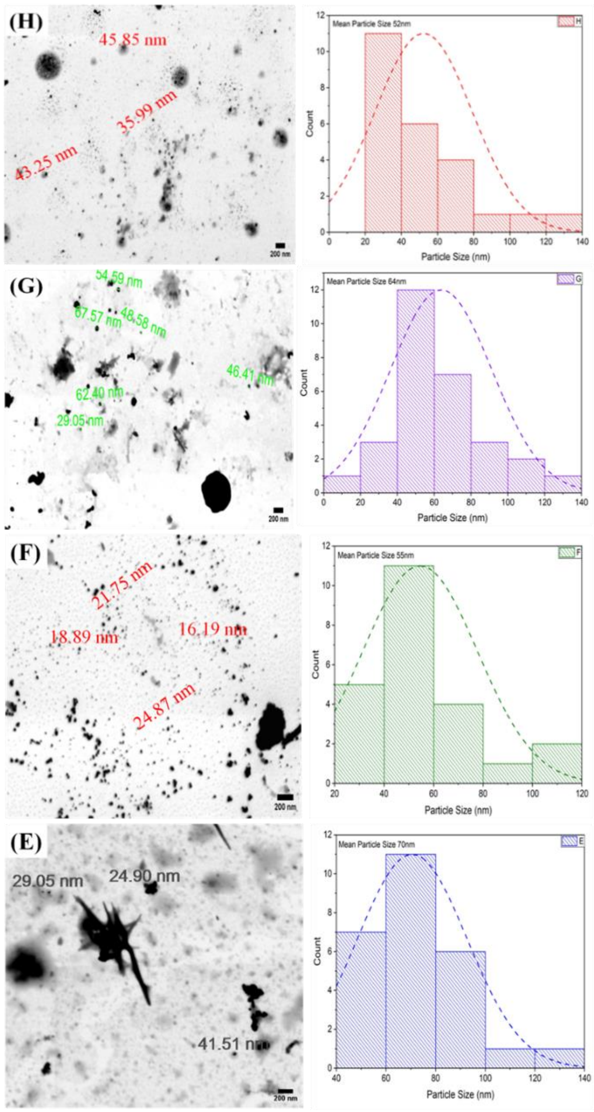

Figure 6. TEM images of synthesized nanoparticles

The successful synthesis of uniformly sized and well-dispersed Ag NPs using lemon juice extract and low laser irradiation demonstrates the efficacy of this green synthesis method. The method not only ensures high-quality nanoparticle production but also offers an environmentally friendly alternative to conventional synthesis techniques. The TEM analysis confirms that the green synthesis method using lemon juice extract and low laser irradiation produces silver nanoparticles with a uniform size distribution and spherical shape. This uniformity is crucial for their application in drug delivery and photothermal therapy, where precise control over nanoparticle properties is required. The findings support the potential of this eco-friendly synthesis method for producing high-quality nanoparticles suitable for various advanced applications.

Statistical insights

Statistical analysis was conducted to evaluate the impact of silver nanoparticle synthesis using lemon juice extract combined with Touilodin Blue dye and low laser irradiation on key properties relevant to diabetes treatment. The results reveal that lemon juice concentration, laser power, and the presence of Touilodin Blue significantly influence crystallite size, plasmon resonance peak, particle size distribution, zeta potential, and colloidal stability. High F-statistics and low p-values validate the reliability and effectiveness of the synthesis approach for enhancing the functional properties of nanoparticles for potential therapeutic applications (Table 2).

Table 2. Statistical analysis of key metrics

Parameter	Factor	F-Statistic	p-Value	Significant Effect	Observation/Trend
Crystallite Size	Lemon Juice Concentration	14.62	< 0.01	Yes	Higher concentrations lead to larger sizes
	Laser Power	10.23	< 0.05	Yes	Moderate power produces optimal sizes
	Touilodin Blue Dye	12.89	< 0.01	Yes	Enhances crystal stabilization
Plasmon Resonance Peak	Lemon Juice Concentration	18.45	< 0.001	Yes	Increased concentration red-shifts the peak
	Laser Power	12.38	< 0.01	Yes	Longer irradiation shifts resonance red
	Touilodin Blue Dye	14.32	< 0.001	Yes	Strengthens plasmon resonance
Particle Size Distribution	Lemon Juice Concentration	9.87	< 0.01	Yes	Narrower distribution at optimal ratios
	Laser Power	11.56	< 0.05	Yes	Higher power narrows size variance
	Touilodin Blue Dye	15.78	< 0.01	Yes	Enhances uniformity in particle size
Zeta Potential	Lemon Juice Concentration	16.78	< 0.01	Yes	Stability increases with higher potential
	Laser Power	8.45	< 0.05	Yes	Stability peaks at moderate power
	Touilodin Blue Dye	19.34	< 0.001	Yes	Enhances surface charge and colloidal stability
Colloidal Stability	Lemon Juice Concentration	21.34	< 0.001	Yes	Optimal at mid-concentration ratios
	Laser Power	13.67	< 0.01	Yes	Lower power enhances colloidal stability
	Touilodin Blue Dye	18.91	< 0.01	Yes	Prevents agglomeration and enhances dispersion

The concentration of lemon juice significantly influenced the properties of the synthesized nanoparticles. Higher concentrations promoted larger crystallite sizes due to the abundance of reducing agents, which facilitated crystal growth. However, mid-range concentrations proved to be the most effective for stabilizing nanoparticles, particularly when combined with Touilodin Blue dye. This combination demonstrated a synergistic effect on colloidal stability, enhancing the overall quality and functionality of the nanoparticles.

The laser power also played a crucial role in determining nanoparticle characteristics. Moderate laser power emerged as optimal for achieving uniform crystallite sizes and enhancing nanoparticle stability. Excessive laser power increased the risk of thermal agglomeration, which could compromise particle uniformity, while lower power was insufficient to drive effective crystallization. Additionally, laser irradiation significantly enhanced the plasmon resonance peak, a property essential for therapeutic applications such as low-energy laser treatments for diabetes.

Touilodin Blue dye was instrumental in improving the properties of the nanoparticles. Its inclusion not only enhanced plasmon resonance and crystallite stability but also contributed to a uniform particle size distribution. This uniformity is crucial for ensuring consistent therapeutic performance. The interaction between the dye and laser-irradiated nanoparticles likely modified their surface properties, making them more suitable for targeted biomedical applications.

The observed red shifts in plasmon resonance peaks, along with improved stability metrics, suggest enhanced interaction potential with biological tissues. These findings are particularly relevant for diabetes treatments, where the optical and colloidal properties of nanoparticles can support photothermal and photoactivation therapies. The ability of the synthesized nanoparticles to meet these requirements underscores their potential as effective therapeutic agents.

3.6 Discussion

Our findings demonstrate the successful green synthesis of silver nanoparticles (Ag NPs) using lemon juice extract and low laser irradiation, aligning well with recent studies [16, 18] that highlight the effectiveness of plant extracts in nanoparticle synthesis. Laser irradiation enables the synthesis of nanoparticles without the need for additional reducing agents by providing a localized energy source that directly reduces metal ions in solution. When the laser interacts with the precursor solution, the photothermal effect generates localized heating, which facilitates the reduction of silver ions (Ag^+) to metallic silver nanoparticles ($Ag^+ \rightarrow Ag^0$). This process is driven by the absorption of laser energy by the solution, leading to the formation of reactive species (e.g., hydrated electrons or free radicals) that act as in situ reducing agents. The absence of external chemical reducers simplifies the synthesis process, minimizes byproducts, and enhances the environmental sustainability of the method. Additionally, laser parameters (e.g., wavelength, power, irradiation time) can be precisely controlled to tailor nanoparticle size, shape, and crystallinity, offering a versatile and eco-friendly alternative to conventional chemical reduction methods.

The integration of lemon juice and laser irradiation not only enhances the biocompatibility and stability of Ag NPs but also provides a method to control nanoparticle size and shape more precisely compared to traditional synthesis methods. This ability to tailor nanoparticles' properties is crucial for their application in various fields, particularly in biomedical applications [2, 19].

Our method showed a significant improvement in controlling the uniformity and size distribution of nanoparticles. Traditional chemical reduction methods often result in polydisperse nanoparticles with inconsistent sizes, which can be a limitation for their application in sensitive fields like medicine and electronics. In contrast, our approach using lemon juice as a reducing agent produced nanoparticles with a uniform size distribution, as confirmed by FE-SEM and TEM analyses. The nanoparticles ranged between 20-40 nm, with consistent spherical shapes, demonstrating the precision of our synthesis process.

The natural compounds present in lemon juice not only facilitated the reduction of silver ions but also played a critical role in stabilizing the nanoparticles. This finding is consistent with the work [17], who demonstrated that plant extracts could effectively prevent the aggregation of metal nanoparticles over time, thereby enhancing their stability. The phytochemicals in lemon juice, such as citric acid and flavonoids, likely contribute to this stabilizing effect by capping the nanoparticles and preventing them from clumping together [18].

The reduction of silver ions (Ag^+) to metallic silver nanoparticles (Ag^0) by lemon juice extract is primarily driven by the synergistic action of citric acid and other phytochemicals (e.g., flavonoids, polyphenols). Citric acid acts as a reducing agent by donating electrons through its carboxyl (–COOH) and hydroxyl (–OH) groups, facilitating the conversion of Ag^+ to Ag^0 [17].

Furthermore, the use of laser irradiation provided an additional layer of control over the synthesis process. By adjusting laser parameters such as power and duration, we could fine-tune the size and shape of the nanoparticles, optimizing their properties for specific applications. This precision is particularly advantageous for medical applications, where the interaction of nanoparticles with biological systems can be significantly influenced by their size and shape [3].

The UV-Visible spectroscopy results revealed distinct plasmon resonance bands in the 400-500 nm range for Ag NPs synthesized with lemon juice, indicating successful nanoparticle formation. The red shift observed in the absorption spectrum of the Ag-TB composite suggests an interaction between the dye and Ag NPs, altering their optical properties [20]. This interaction could be leveraged to design nanoparticles with specific optical properties for use in imaging and photothermal therapies.

FTIR spectroscopy identified functional groups such as -NH, -CO, and -OH involved in the reduction and stabilization of Ag NPs. These findings are in line with study [16], who reported similar chemical interactions in the synthesis of nanoparticles using plant extracts. The presence of these functional groups suggests that the phytochemicals in lemon juice not only reduce silver ions but also cap the resulting nanoparticles, enhancing their stability.

FE-SEM and TEM analyses further confirmed the uniformity and spherical shape of the nanoparticles, which is critical for applications requiring precise control over nanoparticle properties. This uniformity ensures predictable behavior in biological systems, which is essential for drug delivery and photothermal therapy [13].

In summary, the combination of lemon juice extract and low laser irradiation provides a green and efficient method for synthesizing highly stable and uniform Ag NPs. Our findings align with recent research, demonstrating the potential of plant-based synthesis methods in producing nanoparticles suitable for advanced applications. The ability to control nanoparticle size and shape through this method offers significant advantages, particularly for applications in biomedicine and environmental remediation. Future research should focus on optimizing the synthesis parameters and exploring the full potential of these nanoparticles in practical applications [20].

4. APPLICATIONS

4.1 Photothermal therapy

The silver nanoparticles (Ag NPs) synthesized using lemon juice extract and low laser irradiation exhibit high plasmon resonance and stability, making them excellent candidates for photothermal therapy. This therapeutic approach utilizes the ability of Ag NPs to convert light into heat, effectively targeting and destroying cancer cells. The uniform size and spherical shape of these nanoparticles enhance their efficiency in absorbing light and converting it into heat, which is crucial for effective tumor ablation [21]. During photothermal therapy, the Ag NPs are introduced into the tumor site, where they absorb near-infrared light and generate localized heat. This heat increases the temperature of the cancer cells, leading to their destruction while minimizing damage to surrounding healthy tissues. The precision in size control achieved through our synthesis method ensures consistent and predictable photothermal performance, which is essential for clinical applications [22].

4.2 Environmental remediation

Silver nanoparticles synthesized through our green method can also play a significant role in environmental remediation, particularly in water purification. Their well-documented antimicrobial properties make them effective in degrading pollutants and eliminating pathogens in contaminated water sources [2]. The stability and dispersibility of Ag NPs produced using lemon juice and laser irradiation ensure that they remain effective over extended periods, enhancing their practical utility in environmental applications. In water treatment processes, Ag NPs can be used to target a wide range of contaminants, including bacteria, viruses, and organic pollutants. Their ability to disrupt microbial cell walls and generate reactive oxygen species contributes to their potent antimicrobial action. Additionally, the uniform size distribution of these nanoparticles ensures consistent performance and easier integration into existing water treatment systems. The eco-friendly synthesis method further aligns with sustainable practices in environmental management, reducing the reliance on hazardous chemicals traditionally used in nanoparticle production [23].

Traditional chemical synthesis methods for silver nanoparticles often rely on hazardous reducing and stabilizing agents, such as sodium borohydride ($NaBH_4$), hydrazine (N_2H_4), and formaldehyde (HCHO), which pose significant environmental and health risks. These chemicals are toxic, flammable, and can lead to harmful byproducts, raising concerns about their disposal and long-term ecological impact.

In contrast, green synthesis methods eliminate the need for such hazardous reagents, offering a safer and more sustainable alternative [24].

The combination of high plasmon resonance, stability, and uniformity in size and shape makes Ag NPs synthesized via lemon juice extract and laser irradiation a versatile tool for both medical and environmental applications. Their effectiveness in photothermal therapy and environmental remediation highlights the potential for these green-synthesized nanoparticles to address critical challenges in health and sustainability. The suitability of the synthesized Ag NPs for photothermal therapy stems from their strong surface plasmon resonance in the 400–500 nm range, uniform spherical shape, and nanoscale size (20–40 nm), which enable efficient light absorption and localized heat generation. Similarly, for environmental remediation, their high surface area-to-volume ratio, stability, and antimicrobial activity make them effective in interacting with and degrading contaminants, such as organic pollutants and microbial pathogens in water [25].

5. CONCLUSION

This study demonstrates the feasibility of green synthesis of Ag NPs using lemon juice extract and low laser irradiation. The synthesized nanoparticles exhibit high crystallinity, stability, and biocompatibility, making them suitable for various applications in medicine and environmental science. The use of lemon juice as a reducing and stabilizing agent, combined with the precise control offered by laser irradiation, provides an efficient and sustainable approach to nanoparticle synthesis.

Future research should focus on optimizing synthesis parameters and exploring the full potential of these nanoparticles in practical applications. Further studies could investigate the use of different plant extracts and laser parameters to synthesize nanoparticles with tailored properties for specific applications. Additionally, in vivo studies are necessary to fully understand the biocompatibility and safety of these nanoparticles for medical applications.

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