Green Synthesis of Silver Nanoparticles Using *Emblica officinalis* and Their Role in Mercury (II) Chloride Detoxification

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Abstract: In this study, silver nanoparticles (AgNPs) were successfully synthesized using an aqueous extract of Emblica officinalis, serving as a green, sustainable reducing and stabilizing agent. UV-Visible spectrophotometric analysis confirmed the formation of AgNPs, with a distinct surface plasmon resonance (SPR) peak at 382.04 nm, indicative of well-dispersed, spherical nanoparticles with minimal aggregation. The biosynthesized AgNPs were subsequently utilized to evaluate their potential in degrading mercury(II) chloride ($HgCl_2$). Time-dependent UV-Vis analysis revealed a gradual and significant decline in the characteristic absorbance peaks of $HgCl_2$, particularly at 302 nm, over a 48-hour period. This indicates effective degradation and possible reduction of mercury ions, facilitated by the catalytic and adsorptive properties of the nanoparticles. The findings demonstrate the dual functionality of E. officinalis-mediated AgNPs as both nanocatalysts and sorbents, offering a promising, eco-friendly approach for heavy metal remediation in aquatic environments.

***Keywords**: Emblica Officinalis; Silver Nanoparticles; Heavy Metal Remediation.*

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I. INTRODUCTION

Nanotechnology is an interdisciplinary field that has gained immense momentum over the past few decades due to its vast potential in transforming various sectors, including medicine, agriculture, energy, and environmental sciences [1]. Defined as the science and engineering of materials at the nanoscale (1–100 nanometers), nanotechnology focuses on manipulating individual atoms and molecules to create materials with novel and often superior properties compared to their bulk counterparts [2]. These enhanced properties—such as increased surface area-to-volume ratio, quantum effects, and greater catalytic activity—arise due to the reduction in size and the dominance of surface atoms, which render nanomaterials highly reactive and functional in specific environments [3]. The innovation and application of nanomaterialshave become a cornerstone for the development of next-generation technologies, from targeted drug delivery systems and biosensors to clean energy solutions and water purification systems [4].

Among the various types of nanoparticles explored, metallic nanoparticles have garnered significant interest due to their unique physicochemical and biological properties[5]. In particular, silver nanoparticles (AgNPs) have emerged as one of the most widely investigated and utilized nanomaterials. Their remarkable antimicrobial, antifungal, antiviral, and anti-inflammatory activities, coupled with strong optical and catalytic behaviors, have rendered them highly valuable in a wide range of applications [6]. These include their incorporation into wound dressings, coatings for medical devices, textiles, cosmetics, and food packaging materials. Additionally, AgNPs are being explored for their potential in cancer therapeutics, biosensing, and environmental

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remediation, making them one of the most versatile and multifunctional nanoparticles in current research [7].

Conventional methods for synthesizing silver nanoparticles often rely on physical and chemical techniques, such as laser ablation, photochemical reduction, microwave irradiation, and chemical reduction using various stabilizing agents [8]. While effective in controlling size and shape, these methods frequently involve the use of hazardous chemicals, high energy consumption, and complex instrumentation [9]. The production of toxic by-products and the environmental impact of these synthetic routes raise concerns regarding their sustainability, especially when considering large-scale production and biomedical applications. In response to these challenges, green synthesis has emerged as a sustainable, cost-effective, and environmentally friendly alternative for nanoparticle production [10].

Green synthesis of nanoparticles refers to the use of natural sources—primarily plant extracts, microorganisms (bacteria, fungi, algae), and biomolecules—to mediate the reduction of metal ions into nanoparticles [9]. This approach is inspired by the principles of green chemistry, which emphasize the use of non-toxic solvents, renewable materials, and processes that reduce or eliminate the generation of hazardous substances [11]. Among the biological methods, plant-mediated synthesis has received significant attention due to its simplicity, scalability, and the diverse range of phytochemicals present in plant tissues that can act as both reducing and stabilizing agents [12]. These phytochemicals include flavonoids, phenolics, terpenoids, alkaloids, and sugars, which facilitate the efficient conversion of metal salts into nanoparticles without the need for additional chemical reagents [13].

The green synthesis of silver nanoparticles using plant extracts has proven to be an effective and rapid process, typically involving the mixing of an aqueous solution of silver nitrate ($AgNO_3$) with the plant extract [14]. The bioactive compounds in the extract reduce Ag^+ ions to Ag^0, leading to the nucleation and growth of nanoparticles [15]. Factors such as pH, temperature, concentration of the metal salt, and the composition of the plant extract influence the size, shape, and stability of the resulting nanoparticles [16]. One of the major advantages of this method is the ability to tune these parameters to obtain nanoparticles with specific morphologies and properties, making it highly versatile for different applications [17].

The application spectrum of green-synthesized silver nanoparticles is extensive and continually expanding. In the biomedical field, AgNPs have demonstrated potent antibacterial activity against a broad range of Gram-positive and Gram-negative bacteria, including drug-resistant strains [18]. This has led to their use in wound healing products, surgical instruments, and as coatings for implants to prevent infection. Their antifungal and antiviral properties further contribute to their utility in healthcare [19]. Moreover, silver nanoparticles have shown promising results in anticancer research, where they induce apoptosis and inhibit the proliferation of various cancer cell lines. The biocompatibility of green-synthesized nanoparticles makes them particularly suitable for these sensitive applications [20].

In addition to biomedical uses, AgNPs have shown significant potential in agriculture. They can act as effective agents in pest control, reducing the reliance on synthetic pesticides that are often associated with environmental toxicity and resistance issues [21]. When applied in controlled doses, AgNPs can also enhance plant growth by influencing seed germination, nutrient uptake, and resistance to abiotic stress. Their role in agriculture is particularly promising in the context of sustainable farming practices and integrated pest management strategies [22].

Silver nanoparticles have also found applications in environmental science, particularly in water treatment and pollution control. Their strong antimicrobial properties enable them to be used in filters and membranes for the removal of microbial contaminants from drinking water [23]. Furthermore, AgNPs have been incorporated into systems for the detection and removal of heavy metals and organic pollutants, offering a dual function of sensing and remediation. In the realm of energy, silver nanoparticles are utilized in photovoltaic cells and conductive inks due to their excellent electrical conductivity and optical properties [24]. Their inclusion in sensors and nanodevices further expands their technological relevance.

Another area where AgNPs have made a substantial impact is in the field of food packaging and preservation. Incorporation of silver nanoparticles into food packaging materials can extend the shelf life of perishable items by preventing microbial growth [25]. Their use in edible coatings, biodegradable films, and smart packaging systems contributes to improved food safety and reduced food waste. With increasing consumer demand for eco-friendly and sustainable packaging solutions, the integration of green-synthesized nanoparticles in the food industry is gaining considerable attention [26].

While the advantages of green-synthesized silver nanoparticles are numerous, challenges remain in terms of standardization, reproducibility, and large-scale production. Variability in plant extract composition due to seasonal, geographical, and environmental factors can affect the consistency of nanoparticle synthesis [27]. Therefore, detailed characterization using techniques such as UV-Vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) is essential to confirm the formation and assess the properties of

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the synthesized nanoparticles [28]. Advances in analytical techniques and process optimization are critical for translating laboratory-scale green synthesis into commercially viable technologies [29].

The integration of nanotechnology with green chemistry has opened up new avenues for the sustainable production of silver nanoparticles with significant biological and industrial potential [30]. The use of plant-based methods for the synthesis of AgNPs aligns with global efforts to minimize environmental impact and promote the use of renewable resources. As research continues to uncover new plant sources and optimize synthesis conditions, the scope for innovative applications of green-synthesized AgNPs will expand further [31]. With continued interdisciplinary collaboration and technological advancement, green nanotechnology is poised to play a transformative role in the development of safer, cleaner, and more sustainable solutions across diverse domains [32].

II. MATERIAL AND METHODS

A. Plant Collection and Extraction

The *Emblica officinalis* tree leaves were collected from agricultural field in Coutrallam hills. The powder was prepared by shade-drying fresh leaves, followed by grinding into a fine powder using a mechanical grinder. To prepare the leaf extract, 10 grams of dry leaf powder were mixed with 100 mL of distilled water and boiled at 60–80°C for 20 minutes. After boiling, the solution was allowed to cool to room temperature and was then filtered through Whatman No.1 filter paper to obtain a clear extract.

B. Synthesis and Characterization of AgNPs

Dry leaf powder of *Emblica officinalis* was used for the green synthesis of silver nanoparticles. For nanoparticle synthesis, a 1 mM silver nitrate ($AgNO_3$) solution was prepared by dissolving 0.017 grams of $AgNO_3$ in 100 mL of distilled water. In a typical reaction setup, 10 mL of the dry leaf extract was added to 90 mL of the 1 mM$AgNO_3$ solution in a conical flask and kept under continuous stirring at room temperature or slightly elevated temperatures (40–50°C). A visible color change from pale yellow to brown was observed within a few hours, indicating the reduction of silver ions and the formation of silver nanoparticles.

The synthesized silver nanoparticles were characterized primarily by UV-Visible (UV-Vis) spectroscopy. After synthesis, the nanoparticle suspension was subjected to spectral analysis using a UV-Vis spectrophotometer within the wavelength range of 200–1000 nm. A small aliquot of the colloidal silver nanoparticle solution was taken in a quartz cuvette, and the absorption spectrum was recorded at room temperature.

The presence of silver nanoparticles was confirmed by the appearance of a characteristic surface plasmon resonance (SPR) peak, typically observed between 380 and 450 nm, which is indicative of nanoparticle formation due to the collective oscillation of conduction band electrons. To further understand the optical properties, Mie theory was applied to interpret the UV-Vis spectral data. According to Mie theory, the SPR peak position and intensity are influenced by factors such as particle size, shape, and dielectric environment. The experimental absorption spectra were qualitatively compared to theoretical predictions, supporting the spherical shape and nanoscale size of the synthesized silver nanoparticles.

C. Heavy Metal Degradation using Green Synthesized AgNPs

The ability of green-synthesized silver nanoparticles to degrade mercury(II) chloride ($HgCl_2$) was evaluated under controlled laboratory conditions. A stock solution of $HgCl_2$ was prepared by dissolving an appropriate amount of mercury(II) chloride in distilled water to achieve a concentration of 100 mg/L. For the degradation experiment, 50 mL of $HgCl_2$ solution was taken in a 100 mL conical flask, and a measured volume of the freshly synthesized AgNPs suspension (typically 5–10 mL, depending on nanoparticle concentration) was added. The mixture was then maintained under constant stirring at room temperature in the dark to avoid any photochemical reactions. The reaction progress was monitored at regular intervals by withdrawing small aliquots (2–3 mL) and analyzing the absorbance using UV-Visible spectroscopy in the range of 200–1000 nm. A gradual decrease in the characteristic absorption peak intensity of $HgCl_2$ indicated the degradation of mercury ions, attributed to the catalytic and reductive properties of the silver nanoparticles. Control experiments were simultaneously conducted without AgNPs to distinguish the nanoparticle-driven effect. The degradation efficiency was calculated based on the reduction in absorbance over time.

III. RESULTS AND DISCUSSION

The successful synthesis of silver nanoparticles (AgNPs) using *Emblica officinalis* extract was confirmed through UV-Visible spectrophotometry, a primary tool for characterizing the optical properties of nanoparticles. The UV-Vis absorption spectrum of the green-synthesized AgNPs exhibited a prominent peak at 382.04 nm (Figure 1), which is characteristic of the surface plasmon resonance (SPR) of silver nanoparticles. This SPR phenomenon arises from the collective oscillation of conduction electrons in the silver nanoparticles when excited by incident light. The presence of this peak strongly indicates the formation of silver nanoparticles, as bulk silver does not exhibit this feature.

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The observed absorption peak within the range of 380–450 nm is consistent with previously reported SPR bands for silver nanoparticles synthesized using plant-based reducing agents. The narrow and symmetric nature of the peak at 382.04 nm suggests the formation of spherical and uniformly dispersed nanoparticles, as broader or red-shifted peaks are typically associated with larger or aggregated particles. Furthermore, the absence of additional peaks in the higher wavelength region indicates minimal agglomeration and good stability of the synthesized colloid, possibly due to the capping effect of phytochemicals present in the *E. officinalis* extract.

Using the Mie theory, which relates the SPR peak position to the size and dielectric environment of nanoparticles, an estimation of particle size can be made. According to Mie theory and empirical studies, a SPR peak at ~382 nm corresponds to spherical silver nanoparticles with a size typically in the range of 10–25 nm. This correlation assumes a non-aggregated system in an aqueous medium with minimal background absorption. Since Mie theory applies best to spherical particles, the peak shape and position reinforce the inference that the biosynthesized AgNPs are predominantly spherical.

In this context, the phytochemicals from *E. officinalis*, such as ascorbic acid, polyphenols, and flavonoids, likely played a dual role as reducing and stabilizing agents. These biomolecules facilitate the reduction of Ag^+ ions to Ag^0 and simultaneously cap the nanoparticles, preventing their aggregation and contributing to their stability in suspension. The presence of these bioactive molecules may also influence the dielectric environment around the nanoparticles, slightly affecting the SPR band's position.

Overall, the UV-Vis data strongly support the formation of small, spherical, and monodisperse silver nanoparticles through a green synthesis route using *Emblica officinalis* extract.

The optical behavior of mercury(II) chloride ($HgCl_2$) (Figure 2) and its degradation in the presence of green-synthesized silver nanoparticles was investigated using UV-Visible spectrophotometry. The initial UV-Vis spectrum of mercury(II) chloride exhibited two significant absorption peaks at approximately 240 nm and 302 nm, which are characteristic of electronic transitions associated with the Hg^{2+} ion. The peak around 240 nm is likely due to charge transfer transitions from chloride ligands to the mercury ion, whereas the peak near 302 nm suggests $n \rightarrow \sigma^*$ or $d \rightarrow p$ transitions within the $HgCl_2$ complex. These distinct absorbance peaks serve as analytical fingerprints for monitoring the fate of mercury during the degradation process.

Upon treatment with green-synthesized silver nanoparticles, notable spectral changes were observed over time. The time-resolved UV-Vis spectra recorded at intervals ranging from 0 minutes to 48 hours revealed a progressive decline in the absorbance intensity of the mercury peaks, especially the one at 302 nm. This attenuation of absorbance signals indicates a gradual reduction and possible degradation of mercury(II) chloride, likely through redox interactions facilitated by the reactive surface of AgNPs. The reduction in peak height over time signifies the diminishing concentration of $HgCl_2$ in the system, confirming the nanoparticles' role in mercury detoxification (Figure 3).

The maximum degradation was evident at 48 hours(Figure 3), where the original absorbance peaks were significantly suppressed or nearly absent. The degradation efficiency is attributed to the high surface area and catalytic activity of the silver nanoparticles, which may have promoted the reduction of Hg^{2+} ions to less toxic forms, potentially elemental mercury (Hg^0) or mercury nanoparticles, or facilitated complexation with the phytochemicals present on the nanoparticle surface. This interaction disrupts the original $HgCl_2$ electronic structure, resulting in a shift or disappearance of the characteristic UV-Vis peaks.

Moreover, the early stage (0–30 minutes) of the reaction showed only minor changes, indicating that the initial contact and nucleation steps are relatively slow. However, with increased exposure time (60 minutes onward), a consistent decline in absorbance values was noted, reflecting the kinetic progression of the degradation reaction. This trend implies that the silver nanoparticles function not only as a reducing agent but may also serve as a sorbent medium, binding mercury ions and removing them from solution.

These results highlight the potential of green-synthesized AgNPs as effective nanomaterials for the detoxification of mercury pollutants. The decrease in UV-Vis absorption signals with time demonstrates their catalytic and interactive role in altering the chemical environment of mercury species. This study offers a promising eco-friendly approach for heavy metal remediation, utilizing plant-derived silver nanoparticles that are both cost-effective and environmentally sustainable.

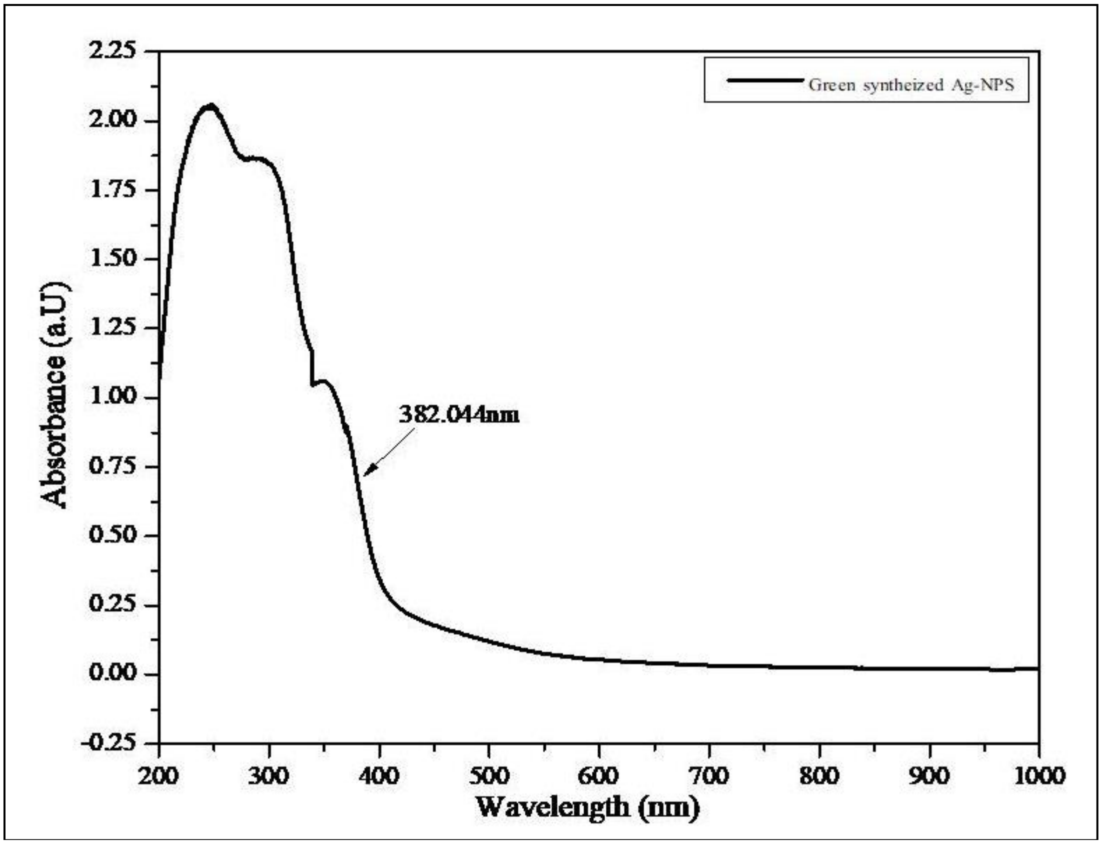

Fig 1: UV/Vis Spectral Analysis of Green Synthesized Silver Nanoparticles.

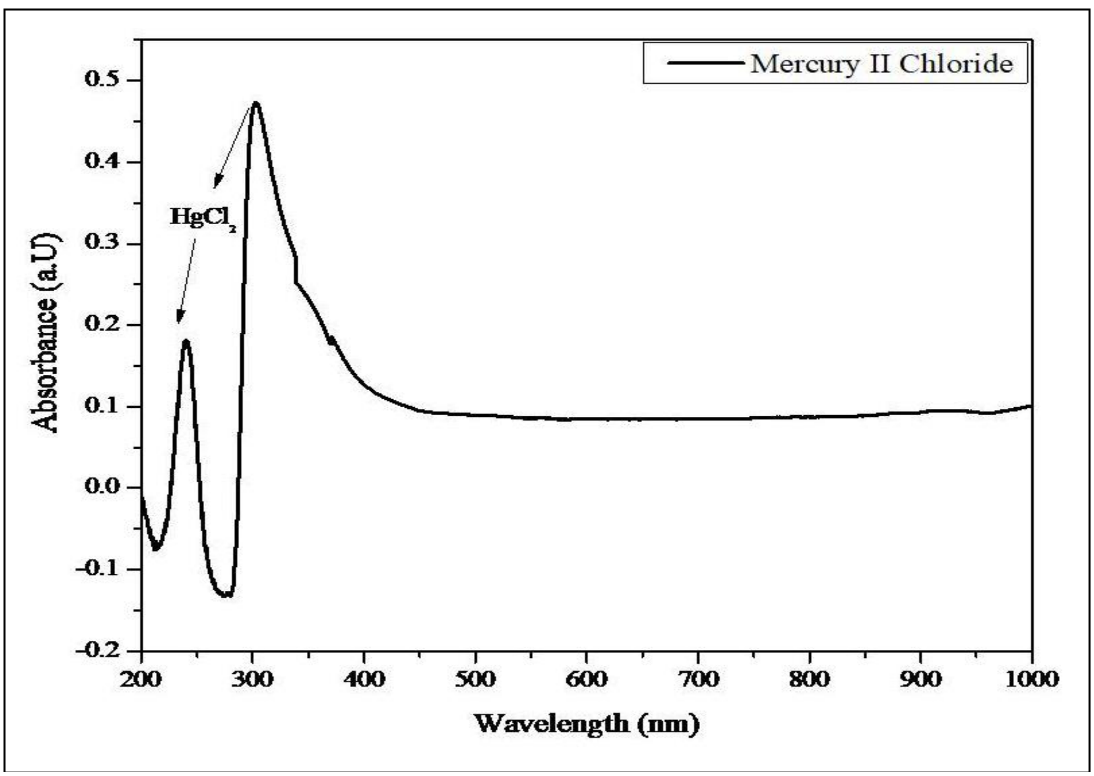

Fig 2: UV/Vis Spectra of Mercury II Chloride.

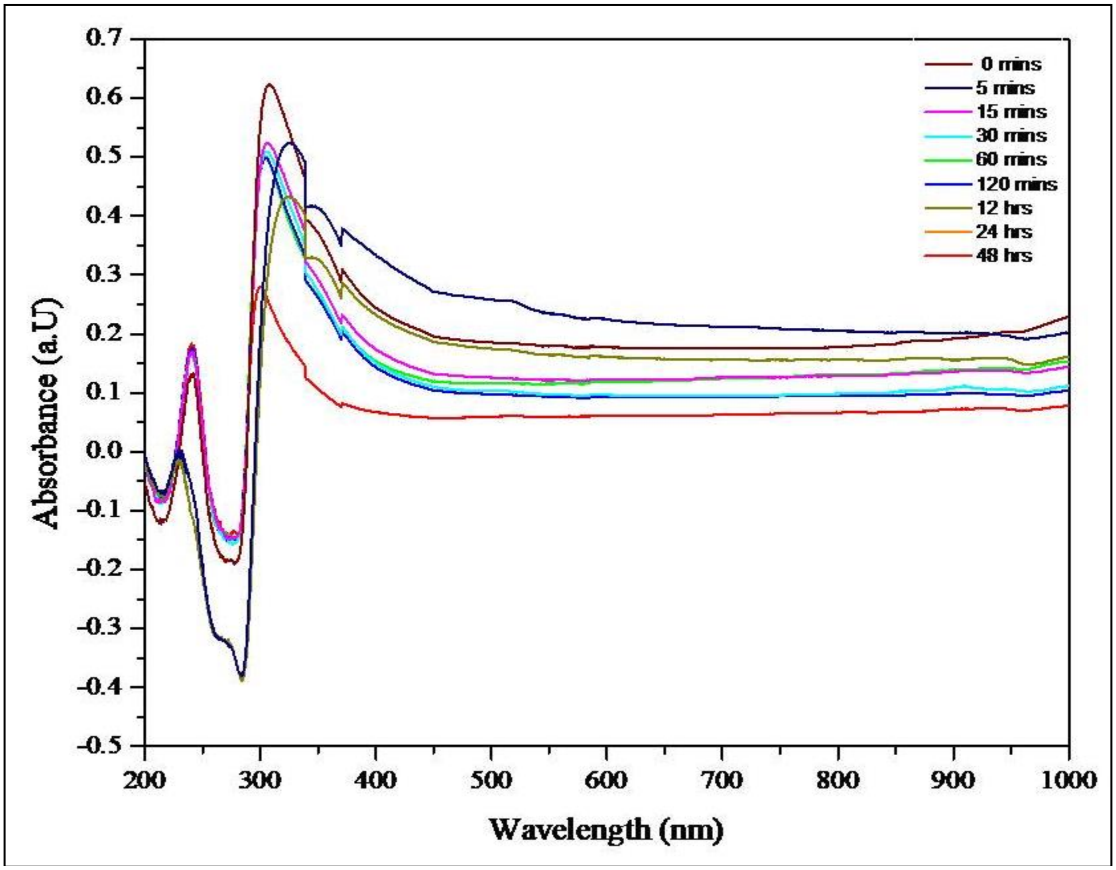

Fig 3: Mercury Degradation of Green Synthesized Silver Nanoparticles.

IV. CONCLUSION

The present study successfully demonstrated the green synthesis of silver nanoparticles (AgNPs) using *Emblica officinalis* extract, as evidenced by the distinct surface plasmon resonance (SPR) peak at 382.04 nm in the UV-Visible spectrum. This peak confirms the formation of small, stable, and predominantly spherical nanoparticles, likely stabilized by the phytochemicals present in the plant extract. The synthesized AgNPs were further evaluated for their efficacy in degrading mercury(II) chloride ($HgCl_2$), a highly toxic heavy metal. Time-dependent UV-Vis analysis revealed a marked decrease in the characteristic absorbance peaks of $HgCl_2$, particularly at 302 nm, indicating progressive degradation over a 48-hour period. This suggests that the biosynthesized AgNPs effectively facilitated the reduction or transformation of mercury ions through redox interactions and possible complexation mechanisms. The findings highlight the dual role of AgNPs as both catalytic and adsorptive agents, underscoring their potential in environmental detoxification. Overall, this green nanotechnology approach provides a sustainable and efficient method for synthesizing functional nanoparticles and mitigating mercury pollution.

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