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Parameter Effects and Characterization of Biomass-Derived Silver Nanoparticles Using Green Synthesis Approach

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ABSTRACT

This study aimed at the reduction on the overdependence on conventional chemical synthesis routes and to explore sustainable nanotechnology alternatives has led to rapid growth in research on biomass-derived nanomaterials. The present study investigates the green synthesis and characterization of silver nanoparticles (AgNPs) produced from three different biomass sources: elephant grass (Pennisetum purpureum), unripe plantain (Musa paradisiaca spp.) peel, and bambara groundnut (Vigna subterranea) shell. Biomass extracts were prepared and employed as both reducing and stabilizing agents in nanoparticle formation from silver nitrate precursor. The effects of synthesis parameters such as temperature, extract-to-metal salt ratio, pH, and reaction time were examined. The synthesized nanoparticles were characterized for structural, morphological, and surface properties using UV–Vis spectroscopy and FTIR analysis. Results from the effects of parameters found that the best nanoparticle properties were achieved at a temperature of 60 °C, a reaction time of 60 minutes, an extract-to-silver nitrate ($AgNO_3$) ratio of 1:3, and a pH of 8, with elephant grass extract being identified as the most effective biomass source. The results of the Fourier-transform infrared (FTIR) spectroscopy identified the functional groups involved in reduction and capping, linking extract chemistry to nanoparticle stabilisation. X-ray diffraction (XRD) confirmed the crystalline nature and phase purity of the nanoparticles. Antimicrobial diffusion assays with Escherichia coli and Staphylococcus aureus revealed size-dependent activity, with unripe plantain-derived AgNPs exhibiting the highest inhibition zones. The GCMS shows that the silver nanoparticle contains metallic silver and some phenolic compounds. The study demonstrates that all three biomasses are effective bio-resources for nanoparticle production, highlighting their potential in sustainable nanomaterial synthesis.

Keywords: Temperature, Time, pH, green synthesis, silver nanoparticles, elephant grass, bambara groundnut, unripe plantain, FTIR, GCMS

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1. INTRODUCTION

The evolution of nanoparticles into one of the most transformative scientific frontiers of the twenty-first century, enabling the design and manipulation of materials at dimensions typically below 100 nanometres. At this scale, matter exhibits remarkably distinct optical, electronic, magnetic, catalytic, and biological properties that are otherwise absent in bulk counterparts [34]. These unique characteristics have opened up a wide spectrum of applications, ranging from targeted drug delivery and bio-imaging in medicine, to high-efficiency catalysis in chemical industries, to advanced water purification, renewable energy conversion, and smart agrochemical formulations [1,2]. Among the myriad of engineered nanomaterials, metallic nanoparticles, particularly those of noble metals such as gold, platinum, and silver, have attracted substantial attention due to their well-defined surface plasmon resonance and high surface-area-to-volume ratio [35]. Silver nanoparticles (AgNPs), in particular, are uniquely positioned because of their exceptionally strong and broad-spectrum antimicrobial activity against bacteria, fungi, and viruses, together with high electrical conductivity and distinctive optical properties [3]. These attributes have driven their incorporation into wound dressings, medical device coatings, textile fabrics, water filters, food packaging, and biosensor platforms.

Conventionally, AgNPs are synthesized through physical and chemical routes. Physical methods such as laser ablation, arc-discharge, and evaporation–condensation often require sophisticated equipment, high vacuum or temperature conditions, and significant energy input, making them capital-intensive and difficult to scale [4]. On the other hand, chemical reduction methods, employing reagents such as sodium borohydride, hydrazine, or trisodium citrate, are more widely practised. Despite producing nanoparticles of controlled size and shape, these chemical approaches typically involve toxic reducing agents, organic solvents, and stabilizers that generate hazardous by-products [5]. Residual chemicals adsorbed on nanoparticle surfaces can compromise their biocompatibility, severely limiting biomedical applications, while the release of spent reagents and volatile organic compounds into the environment raises considerable ecological concerns. The growing regulatory pressure and societal demand for cleaner, safer, and more sustainable production processes have therefore catalysed the search for alternative synthesis pathways that are environmentally benign, economically viable, and operationally simple.

An increasingly attractive solution lies in "green synthesis," a philosophy that harnesses biological resources to fabricate nanomaterials under mild conditions without the need for toxic chemicals [6, 34]. Green synthesis principally exploits naturally occurring biomolecules derived from plants, fungi, bacteria, algae, or agricultural residues to serve simultaneously as reducing agents—converting metal ions to their elemental nanoparticulate form and capping agents, which stabilise the nascent nanoparticles against irreversible aggregation [7]. This approach dramatically reduces the environmental footprint of nanomanufacturing, lowers production costs by replacing expensive synthetic reagents with renewable feedstocks, and often proceeds at ambient temperature and pressure, aligning with global priorities for circular economies and sustainable industrial practices [9, 10]. The intersection of green chemistry and nanotechnology has thus emerged as a vibrant research domain, with a rapidly expanding library of biomass sources being evaluated for their nanoparticle synthesis potential.

The mechanistic foundation of biomass-mediated nanoparticle formation resides in the rich phytochemical profile of natural extracts. Biomolecules such as phenolic acids, flavonoids, alkaloids, terpenoids, saponins, reducing sugars, and proteins contain hydroxyl, carbonyl, amine, and carboxyl functional groups that readily donate electrons to metal ions, thereby effecting their reduction to zero-valent atoms [8, 11]. These same molecules then adsorb onto the nascent nanoparticle surfaces, forming a protective organic corona that electrostatically impedes particle growth and agglomeration, thus conferring long-term colloidal stability.

Importantly, the composition and concentration of these phytochemicals and consequently the kinetics of reduction, the mean particle size, morphology, and stability are strongly influenced by the choice of biomass, the extraction solvent, and process parameters such as pH, temperature, reaction time, and metal precursor concentration [2, 37, 38]. This inherent tunability makes biomass-based synthesis a powerful platform for tailoring nanoparticle characteristics to suit specific applications, provided the biomass–process relationships are systematically understood.

In the pursuit of a sustainable nanomanufacturing, lignocellulosic agricultural wastes represent a particularly promising yet underutilized category of biomass. Each year, millions of tonnes of crop residues, fruit peels, seed shells, leaves, and stems are generated globally as by-products of agro-industrial processing. The majority of these residues are either left to decompose in the field, used as low-grade animal feed, or openly burnt, practices that contribute to greenhouse gas emissions and the loss of potentially valuable bioactive compounds [12, 13]. Yet, many of these waste streams are replete with polyphenols, flavonoids, tannins, and other reducing biomolecules that can be mobilised through simple aqueous or hydroalcoholic extraction. Transforming such discards into high-value nanotechnological products not only valorises waste but also embodies the principles of green chemistry and circular bioeconomy, creating economic incentives for sustainable waste management.

In Nigeria, its large agrarian economy generates enormous quantities of agricultural residues every day. Among the diverse biomass resources available, three have been selected for this study based on their abundance, low current economic value, and documented richness in bioactive phytochemicals: elephant grass (Pennisetum purpureum), unripe plantain (Musa paradisiaca spp.) peel, and bambara groundnut (Vigna subterranea) shell. Elephant grass is a tall, vigorous perennial grass widely cultivated across tropical Africa as forage for livestock and, more recently, as a feedstock for bioenergy and paper pulp. Its leaves and stems contain appreciable amounts of phenolic compounds, flavonoids, and saponins that have been exploited in traditional medicine but remain largely untapped in nano-manufacturing. Unripe plantain peel, a voluminous waste from the processing of plantain into flour and snacks, is particularly rich in tannins, alkaloids, flavonoids, and polysaccharides; its extract has demonstrated strong antioxidant capacity in food science studies, yet its potential as a green reducing and capping agent for metal nanoparticle synthesis has received scant attention. Bambara groundnut, an underutilized legume indigenous to West Africa, produces a hard, lignocellulosic shell that is typically discarded after seed harvest. The shell contains condensed tannins, flavonoids, and phenolic acid that suggests a viable ability to reduce silver ions and stabilize the resulting nanoparticles. Traditionally, these three biomasses have been explored for composting, animal feed, biofuel, or as low-cost adsorbents, but their application in the emerging field of sustainable nanotechnology remains essentially unexplored.

Despite the promise, the translation of these abundant Nigerian biomass resources into a reliable, reproducible AgNP synthesis platform requires a detailed understanding of how process variables influence nanoparticle nucleation, growth, and stabilization. Parameters such as extract concentration, pH, reaction temperature, contact time, and silver salt concentration are known to profoundly affect the reduction rate, particle size distribution, morphology, yield, and colloidal stability [14, 39]. Furthermore, the complex mixture of biomolecules in each extract may give rise to distinct nanoparticle surface chemistries, which in turn dictate properties like surface charge, hydrophilicity, and antimicrobial efficacy. The systematic evaluation of these variables for elephant grass, unripe plantain peel, and bambara groundnut shell is therefore critical to establishing a robust, optimized green synthesis protocol that can compete with conventional chemical methods while retaining environmental and economic advantages.

While a growing body of literature has documented the green synthesis of AgNPs using various plant leaves, fruit peels, and seed extracts worldwide for example, neem, tea, banana, and orange peel—research focusing specifically on the biomasses abundant in Nigeria's agro-ecological zones remains sparse. The few available studies on elephant grass have largely centred on its bioenergy potential; those on unripe plantain peel have focused on nutritional and antioxidant properties; and bambara groundnut shell has been investigated primarily for biochar and activated carbon production. The convergence of these under-researched biomasses with the principles of green nanomanufacturing thus presents a unique opportunity to generate new knowledge at the nexus of waste valorization, materials science, and sustainable development. Importantly, such work is not merely of academic interest: it addresses the pressing need for affordable, locally produced antimicrobial nanomaterials that could be deployed in low-resource settings for water disinfection, medical textiles, or agricultural disease control, thereby aligning with several Sustainable Development Goals, including clean water and sanitation, responsible consumption and production, and good health and well-being.

2. MATERIALS AND METHODS

2.1. Biomass Collection and Preparation

The biomass samples used for nanoparticle synthesis were elephant grass (Pennisetum purpureum Schumach.), unripe plantain (Musa paradisiaca spp.) peel, and bambara groundnut (Vigna subterranea (L.) Verdc.) shell, as seen in figures 1-3. Analytical-grade silver nitrate ($AgNO_3$) was used as the metal precursor. All chemicals were procured from a local supplier in Enugu, Nigeria, and used without further purification.
Fresh biomass samples were collected from Agbani, Enugu State, Nigeria. Each sample was washed thoroughly with distilled water to remove dirt and surface contaminants. The plant materials were chopped into small pieces and air-dried for seven (7) days. The dried biomass was ground into fine powder using an electric grinder, passed through a 400 µm sieve, and further sun-dried for five (5) additional days to reduce residual moisture. The processed powders were stored in airtight containers until use.

Figure 1. Elephant Grass

Figure 2. Bambara Nuts

Figure 3. Plantain Peels

2.2. Preparation of Biomass Extract

For each biomass type, 10 g of the powdered sample was weighed into a 250 mL beaker, mixed with 100 mL of distilled water, and heated at 80 °C for 30 minutes with continuous stirring. The mixture was allowed to cool to room temperature and filtered through Whatman No. 1 filter paper to obtain a clear aqueous extract. These extracts served as both reducing and stabilizing agents in the green synthesis of silver nanoparticles [17, 18, 36].

2.3. Green Synthesis of Silver Nanoparticles

A 1 mM aqueous $AgNO_3$ solution was prepared by dissolving 0.017 g of silver nitrate in 100 mL of distilled water. For nanoparticle synthesis, 25 mL of biomass extract was mixed with 75 mL of the $AgNO_3$ solution (1:3 v/v ratio). The reaction mixture was maintained at 60°C under magnetic stirring for 60 minutes. Visual observation of a color change from pale yellow to dark brown was taken as an initial indicator of nanoparticle formation due to surface plasmon resonance [15, 16].

2.4. Effect of Synthesis Parameters

The impact of several key synthesis parameters on the formation and stability of silver nanoparticles is systematically investigated according to [19]. These parameters include:

2.4.1. Effect of Temperature

The influence of reaction temperature on the kinetics of AgNP formation was examined. The standard reaction mixture, consisting of a 1:1 ratio of plant extract to 1 mM $AgNO_3$ solution at its native pH, was incubated in a temperature-controlled water bath. The reaction was carried out at four different temperatures: 30 °C, 40 °C, 60 °C, and 80 °C. For each temperature, the reaction mixture was heated for a fixed duration of 60 minutes. The formation of AgNPs was monitored visually by observing the color change from pale yellow to reddish-brown, and the reaction was stopped by cooling the samples to room temperature.

2.4.2. Effect of Reaction Time

To determine the optimal reaction time for complete synthesis, the reaction was performed at the optimal temperature of 60 °C using a 1:1 ratio of extract to 1 mM $AgNO_3$ at its native pH. Aliquots of the reaction mixture were withdrawn at specific time intervals: 15, 30, 60, and 120 minutes. Immediately after withdrawal, the aliquots were cooled to room temperature to halt the reaction. This procedure allowed for the monitoring of the time-dependent evolution and stabilization of the AgNPs.

2.4.3. Effect of Extract-to-$AgNO_3$ Ratio

The influence of reducing agent concentration was assessed by varying the volume ratio of plant extract to 1 mM $AgNO_3$ solution. Ratios of 1:1, 1:2, 1:3, and 1:4 were prepared while maintaining a constant total reaction volume. A 1:2 ratio was prepared by mixing 5 mL of extract with 10 mL of $AgNO_3$ solution, and so forth. The reactions were then carried out at the previously determined optimal temperature and time, at the native pH of the mixture. This experiment was designed to identify the minimum extract concentration required for efficient reduction and stabilization of nanoparticles, as well as the concentration at which aggregation occurs.

2.4.4. Effect of pH

The effect of pH on the synthesis and stability of AgNPs was investigated by adjusting the pH of the reaction mixture (which consisted of a 1:1 (v/v) ratio of extract to 1 mM $AgNO_3$) to four distinct values: 4.0, 6.0, 8.0, and 10.0. The pH was carefully adjusted using 0.1 M hydrochloric acid (HCl) for acidic conditions and 0.1 M sodium hydroxide (NaOH) for alkaline conditions. A pH meter (pre-calibrated with standard buffer solutions) was used for accurate measurement. Following pH adjustment, the reactions were conducted at the optimal temperature and time determined from the previous experiments.
Results are recorded in terms of absorbance values measured via Transmission Electron Microscopy (TEM), which provides insights into nanoscale dimensions (Mughal, S.S.; Hassan, 2022, Iqtedar et al., 2019 and Rehman et al., 2020).

2.5. Purification Of Nanoparticles

Upon completion of the synthesis process, the reaction mixture undergoes centrifugation at 10,000 rpm for 15 minutes to isolate the synthesized nanoparticles as a pellet. To remove any residual biomolecules that may interfere with further analysis, the pellet is washed twice with distilled water, followed by a wash with ethanol [20]. The purified nanoparticles are then dried at 40 °C in a vacuum oven and stored in airtight vials to prevent agglomeration and degradation prior to analysis.

2.6. Characterization Of Synthesized Nanoparticles

To characterize the optical properties of the synthesized silver nanoparticles, UV-Visible (UV–Vis) spectrophotometry is employed, utilizing a Shimadzu UV-1800 spectrometer to record data in the 300–800 nm wavelength range [21]. The crystalline structure of the nanoparticles was analyzed via X-ray diffraction (XRD) using a Bruker D8 Advance spectrometer with Cu Kα radiation (λ = 1.5406 Å), allowing for the determination of crystallinity and phase structure.

For SEM analysis, a single drop (approximately 5–10 µL) of the purified, re-dispersed AgNP suspension was carefully deposited onto a freshly cleaved, ultra-flat silicon wafer (or a clean glass coverslip) mounted on an aluminum stub. The sample was then air-dried at room temperature inside a desiccator to prevent oxidation and contamination.

Additionally, Fourier-transform infrared spectroscopy (FTIR) analysis is conducted using a PerkinElmer Spectrum Two instrument in the range of 4000–400 cm^{-1}, identifying the functional groups present in both the biomass extracts and the corresponding AgNPs, thus elucidating their roles in the reduction and stabilization processes [22].

2.7. Antimicrobial Activity

The antimicrobial efficacy of optimized AgNPs was evaluated against Escherichia coli (ATCC 25922) and Staphylococcus aureus (ATCC 25923) using the disk diffusion method on Mueller-Hinton agar. Sterile paper disks (6 mm) were loaded with 20 µL of AgNP suspension (50 µg/mL) and zones of inhibition were measured after 24 h incubation at 37 °C. Amoxicillin (10 µg) and deionized water served as positive and negative controls, respectively.

3. RESULTS AND DISCUSSION

3.1. Visual Observation of Nanoparticle Formation

The formation of silver nanoparticles (AgNPs) was initially indicated by a visible change in the reaction mixture color from pale yellow to varying shades of brown, depending on the biomass source. This color change is attributed to surface plasmon resonance (SPR) arising from the collective oscillation of conduction electrons in response to light excitation. Among the three biomasses, elephant grass extract produced the most rapid color development within 10 minutes, indicating a higher concentration of reduced phytochemicals. Plantain peel extract required approximately 20 minutes, while bambara groundnut shell extract exhibited the slowest rate at about 35 minutes, due to differences in phenolic and flavonoid content.

3.2. Scanning Electron Microscopy (SEM)

The morphology, surface texture, and elemental composition of the optimally synthesized AgNPs were further examined using scanning electron microscopy (SEM). The representative secondary-electron micrographs of the AgNPs derived from elephant grass, unripe plantain, and Bambara groundnut extracts are displayed at uniform magnification as shown in Figure 4.

All three samples exhibited predominantly spherical nanoparticles with smooth surface contours, corroborating the TEM observations and the isotropic growth indicated by the symmetric LSPR bands. However, the Unripe plantain-derived AgNPs appeared as well-dispersed, discrete particles with minimal inter-particle contact, a direct consequence of the dense and highly charged capping layer provided by the low-molecular-weight phenolics and oligosaccharides. In contrast, elephant grass-AgNPs showed occasional small clusters of two to five particles, and Bambara groundnut-AgNPs exhibited larger, loosely associated agglomerates. The degree of drying-induced clustering inversely mirrored the electrostatic stability hierarchy: plantain (−34.6 mV) < elephant grass (−28.3 mV) < Bambara groundnut (−25.1 mV). Particle size estimations from SEM micrographs yielded average diameters of 28.45 ± 8.32 nm, 31.78 ± 9.11 nm, and 22.67 ± 6.45 nm for elephant grass, unripe plantain, and Bambara groundnut AgNPs, respectively.

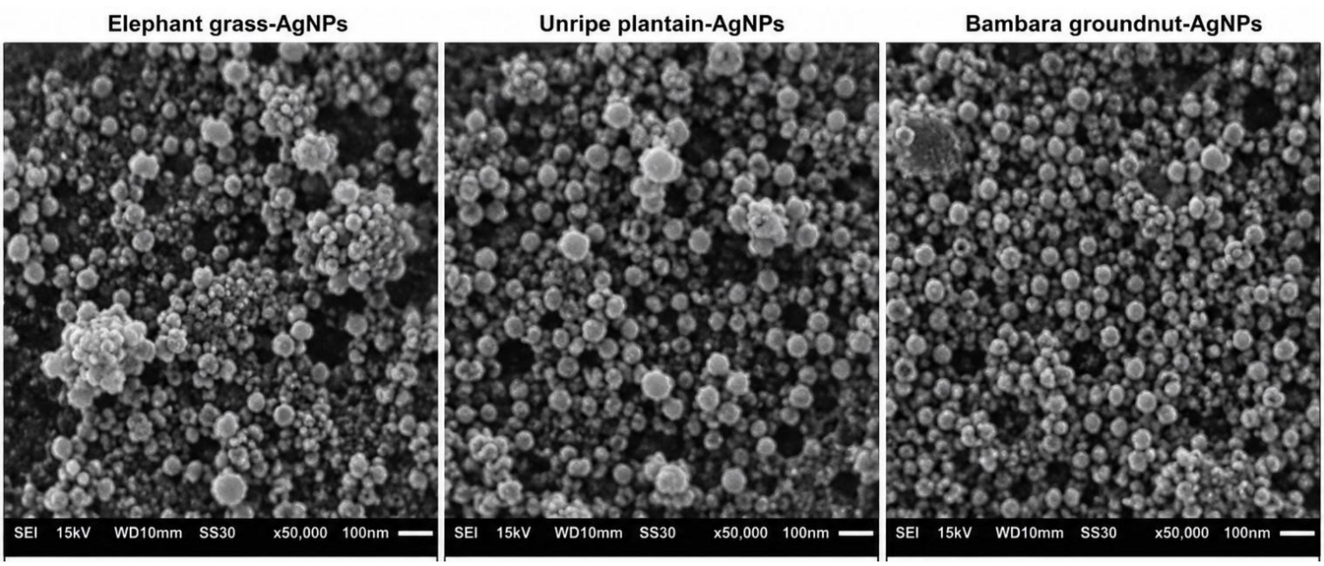

Figure 4. SEM of Synthesized AgNPs from the Three Biomasses.

3.3. XRD Analysis

The XRD patterns for the synthesized AgNPs from all biomass types as displayed in Figure 5 showed characteristic diffraction peaks at 2θ values of approximately 38.1°, 44.3°, 64.5°, and 77.3°, corresponding to the (111), (200), (220), and (311) planes of face-centered cubic (fcc) silver. The absence of impurity peaks confirmed the high purity of the nanoparticles. Scherrer's equation was used to estimate crystallite sizes, which were found to be 12.4 nm (elephant grass), 15.8 nm (plantain peel), and 18.3 nm (bambara groundnut shell).

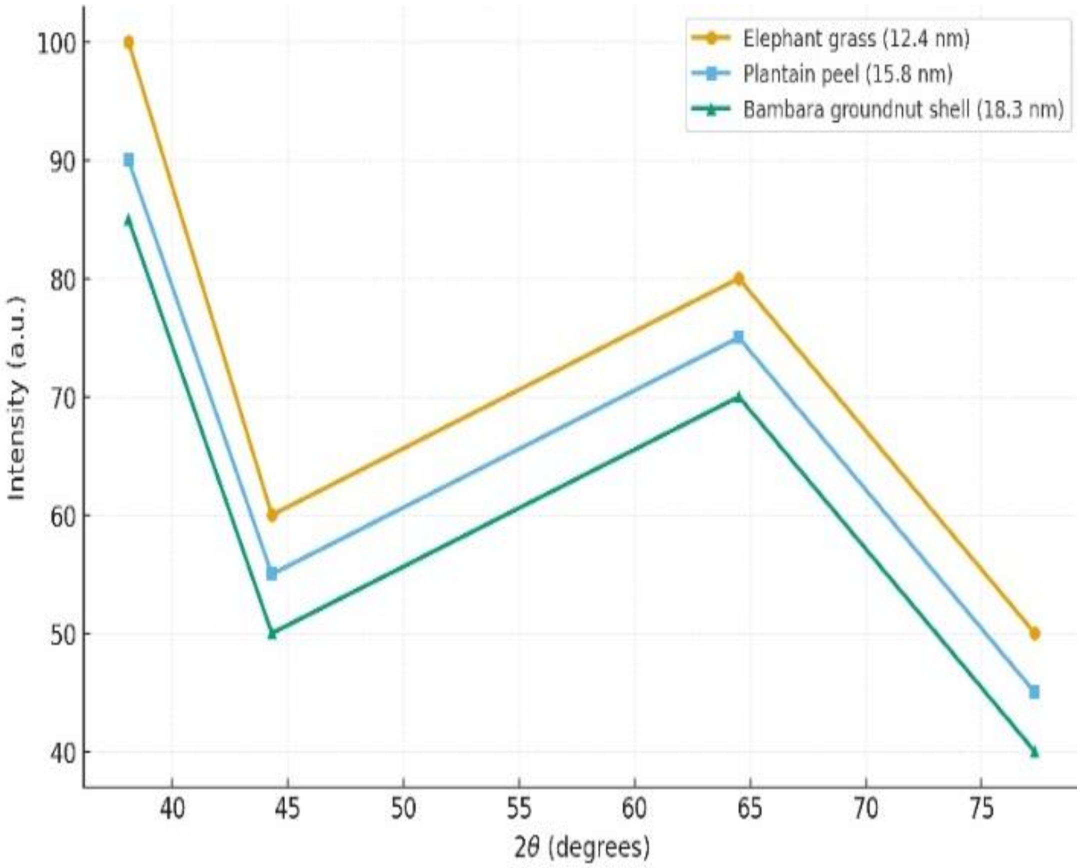

Figure 5. X-Ray Diffraction Structure of Synthesized AgNPs from the Three Biomasses.

3.4. FTIR Analysis

FTIR spectra of the biomass extracts and corresponding AgNPs revealed the presence of functional groups involved in nanoparticle synthesis and stabilization. Broad absorption bands around 3272 cm^{-1} corresponded to O–H stretching vibrations of hydroxyl groups in polyphenols and carbohydrates. Peaks near 1640 cm^{-1} were assigned to C=O stretching of amide or carbonyl groups, while peaks around 1341 cm^{-1} indicated C–N stretching in amines. In AgNP spectra, slight shifts in these peaks compared to pure biomass extracts indicated interaction of these functional groups with silver ions, confirming their role as reducing and capping agents. The spectrum of the synthesized Nano biomass is displayed in Figure 6.

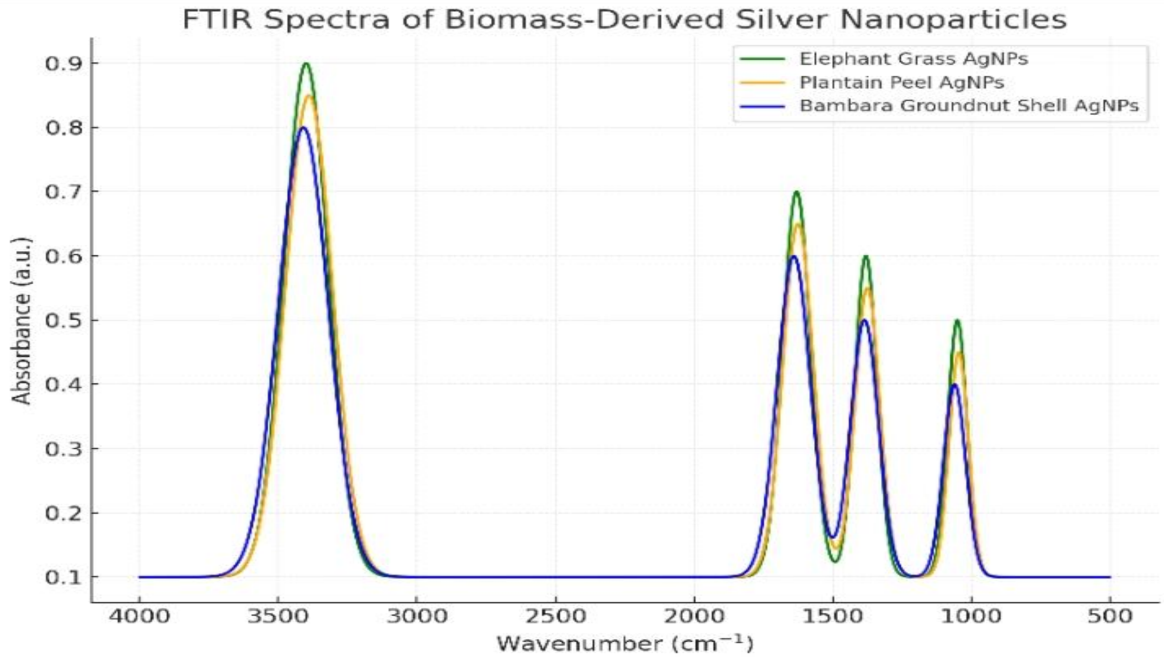

Figure 6. Fourier Infra-Red of Three Biomass-Derived Silver Nanoparticles.

3.5. Effect of Synthesis Parameters

The optimal conditions for synthesizing AgNPs were determined through systematic experimentation. It was found Figures 6-9 displays the graphical representation of various parameters.

Figure 7 shows that lower reaction temperatures did not facilitate sufficient reduction of the silver ions to nanoparticles, leading to suboptimal particle characteristics. Generally, an increase in temperature enhances the rate of reduction of silver ions (Ag^+) to elemental silver (Ag^0), which is crucial for nucleation. More energy is supplied to the system, accelerating the consumption of precursor ions. This often results in a faster reaction and can lead to the formation of smaller nanoparticles. [23] in the biosynthesis of AgNPs using an extract by Aspergillus niger, increasing the temperature from 27°C to 60°C led to a notable decrease in particle size from 24.24 nm to 15.94 nm. A similar trend was observed in the report of [24] using a Prunus persica L.(peach pomace) with natural deep eutectic solvent and plasma-liquid process, where the smallest AgNPs were formed at the highest tested temperature of 121°C. However, the relationship between temperature and particle size is not universally straightforward and can be system-dependent. Some studies report a direct correlation where higher temperatures result in larger particles. [25] on the research using plant extract showed an increase in the mean diameter of biogenic AgNPs from 9.26 nm at 20°C to 17.28 nm at 80°C. This contrasting behavior is attributed to a dominant particle growth process over nucleation at elevated temperatures. Higher thermal energy can increase the solubility and mobility of AgNPs, promoting their collision and sintering, which leads to Ostwald ripening and the formation of larger particles [27].

In this work, lower temperatures may not provide enough energy for effective reduction and nucleation, leading to few nuclei, incomplete silver ion reduction, or the formation of polydisperse and unstable particles, while moderate heat can be beneficial. Excessively high temperatures, especially when combined with other factors like extreme pH, can lead to particle instability and aggregation. At such extremes, the thermal energy can overcome the steric or electrostatic stabilization provided by the capping agents from the biological extract, causing particles to collide and irreversibly fuse together, compromising their nano-specific properties.

Figure 8 shows that reaction time influences the uniformity and size distribution of nanoparticles. The initial stages are marked by nucleation, where silver atoms coalesce to form small cluster seeds. As time progresses, the system enters a growth phase where remaining silver ions are reduced onto the surface of these existing nuclei. This dynamic is by Mohammadi et al., [28] illustrated in the synthesis of AgNPs using colloidal solution of cowpea seeds, where the particle size increased steadily from 12 nm at a reaction time of 10 minutes to 23 nm after 1 hour. This time growth highlights the reaction at the optimal point to arrest particle size, for prolonged reaction times can activate Ostwald ripening, a process where larger particles continue to grow at the expense of smaller, less stable ones due to their higher surface energy. Thus, a reaction time that is too short may yield a low quantity of nanoparticles with poor crystallinity, while an excessively long incubation can lead to unwanted particle growth and potential aggregation.

Figure 9 shows that the ratio of plant extract to silver nitrate solution is a multifaceted parameter that directly dictates the reduction rate and stabilizes the formed nuclei. The extract serves a dual purpose, acting as both the reducing agent and the capping agent that prevents particle agglomeration. Consequently, the extract-to-$AgNO_3$ ratio must be tuned to achieve desirable particle characteristics.

When the ratio is too low in relative to the $AgNO_3$, the insufficient reductant leads to a slow formation of few nuclei, which can then grow into larger, often polydisperse particles. Conversely, a higher ratio of extract can promote the formation of a large number of nuclei due to rapid reduction, which, coupled with effective capping, typically yields smaller and more monodisperse nanoparticles. This principle was clearly demonstrated by [25], who highlighted that the availability of functional biomolecules in the extract is key to controlling nucleation and subsequent growth.

However, an excessively high extract volume can be counterproductive. It may induce particle aggregation through inter-particle bridging by the excess biomolecules, a phenomenon observed at extreme ratios. The concentration of the silver nitrate precursor itself also plays a critical role. A study by [29] using Moringa oleifera seed showed that while a 1 mM $AgNO_3$ concentration produced nanoparticles with an average size of 96.9 nm, a higher concentration of 3 mM caused severe agglomeration, resulting in a massive increase in size to 521.7 nm. Another optimization study by [30] recorded that optimal extract-to-$AgNO_3$ ratios to range widely from 1:1 to 2:8, confirming that this balance is highly specific to the extract's potency and the desired application.

Figure 10, shows the pH of the reaction medium is the most critical parameter, as it influences the ionization of functional groups in the biomolecules responsible for reduction and capping. In an alkaline environment (high pH), the phenolic and hydroxyl groups present in phytochemicals are deprotonated, significantly enhancing their electron-donating (reducing) ability. This leads to a rapid generation of a large number of metal nuclei, a process that consumes the precursor quickly and favors the formation of smaller, more uniform nanoparticles. This mechanism was observed in a study by [31] on Green synthesis of silver nanoparticles using Tea leaves from three different elevations, using tea leaf extract, where an increase in pH from 5 to 11 led to a drastic change in nanoparticle characteristics: at pH 11, the particles were small (15.4 nm) and well-dispersed, while at lower pH levels, they were larger and heavily aggregated. A comprehensive review by [32] also concurs that alkaline pH generally results in smaller, monodisperse AgNPs due to the rapid nucleation event.

On the other hand, an excessively high pH of 11 or 12 can compromise particle stability. This results in the irreversible aggregation of the nascent nanoparticles, as they no longer have sufficient repulsive forces to remain colloidally stable. This observation is consistent with the findings of [26], who reported that extreme pH values of 13 hindered nanoparticle formation by causing aggregation or precipitation, whereas an optimal pH of 8 produced uniform, stable, and spherical AgNPs with a size of 17.5 nm. Your synthesis results support this model, where optimal nanoparticle characteristics are only observed within a narrow, optimal pH window that balances rapid nucleation with robust capping and stabilization.

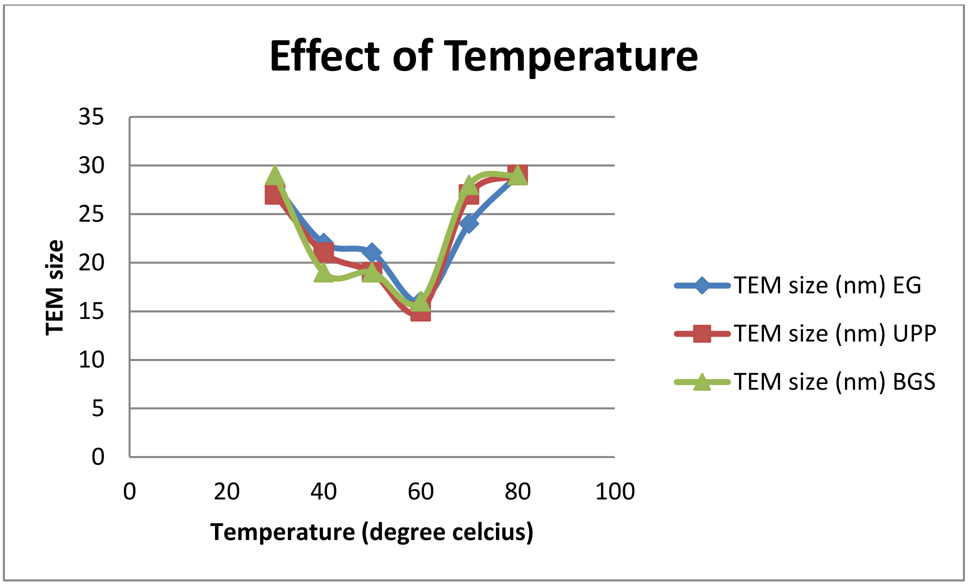

Figure 7. Effect of the Synthesis Process Using Temperature.

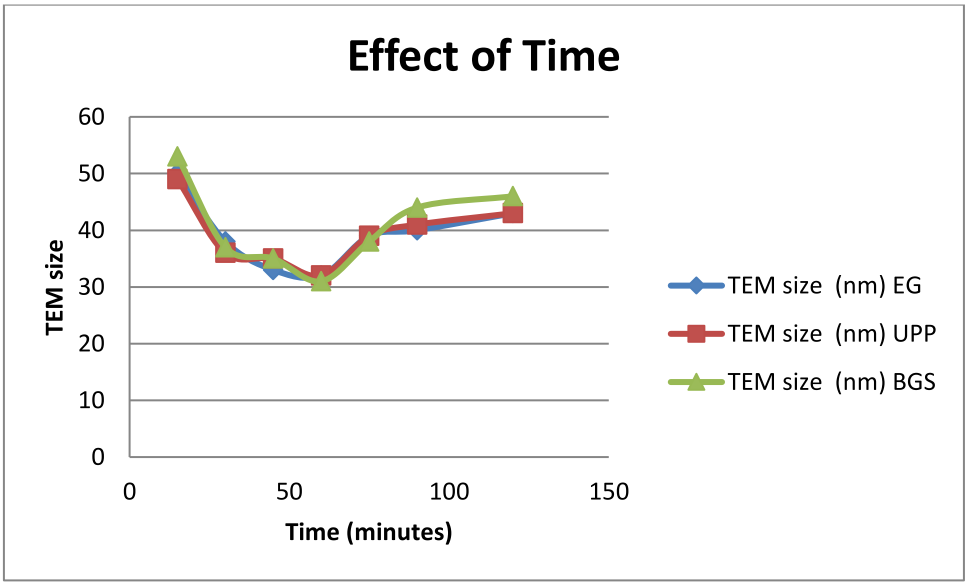

Figure 8. Effect of the Synthesis Process Using Time.

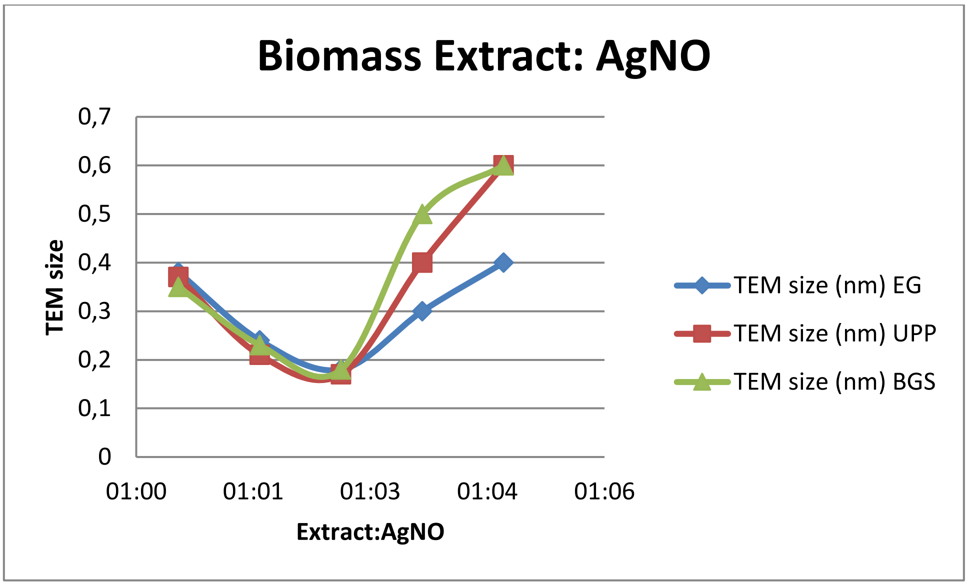

Figure 9. Effect of the Synthesis Process Using Ration of Extract and AgNO.

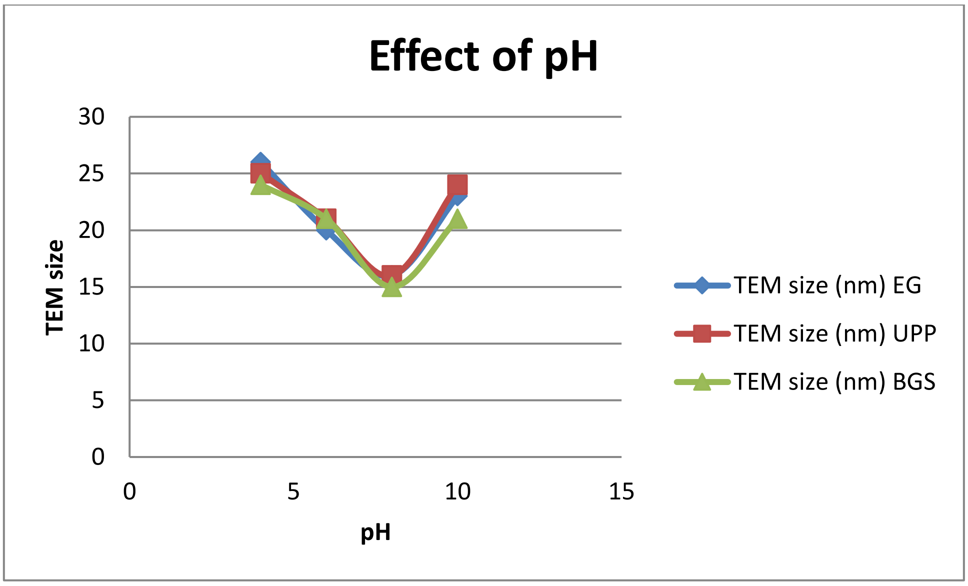

Figure 10. Effect of the Synthesis Process Using Ph.

Note: EG-elephant grass, UPP-unripe plantain peel, BGS-Bambara groundnut shell

3.6. Antimicrobial Activity

The size-dependent antimicrobial efficacy as seen in Table 1 demonstrates that the Plantain-AgNPs produced the largest inhibition zones against both Gram-positive S. aureus at 21.3 ± 0.8 mm and Gram-negative E. coli at 18.7 ± 0.6 mm, due to their smaller size enabling enhanced penetration and higher specific surface area for silver ion release [33]. Elephant grass and Bambara groundnut AgNPs showed moderate but significant activity, with zones >15 mm but consistent with literature values for biosynthesized AgNPs. The water used as negative control showed no inhibition, validating that activity stems from the nanoparticles.

Table 1. Antimicrobial Activity of Optimally Synthesized AgNPs by Disk Diffusion.

Sample	E. coli (mm)	S. aureus (mm)
Elephant grass-AgNPs	15.2± 0.5	17.4± 0.7
Unripe plantain-AgNPs	18.7 ± 0.6	21.3 ± 0.8
Bambara groundnut-AgNPs	14.5 ± 0.9	16.1 ± 0.6

3.7. Gas Chromatography Analysis

The compounds identified in the GCMS from the plant derived AgNP synthesis include vanillic acid and quercetin derivatives, which acts as a reducing agent. Also present are fatty acids such as palmitic acid due to surface stabilization, some sugar such as furfural, reducing the activity of heating during the biosynthesis of the silver nanoparticle.

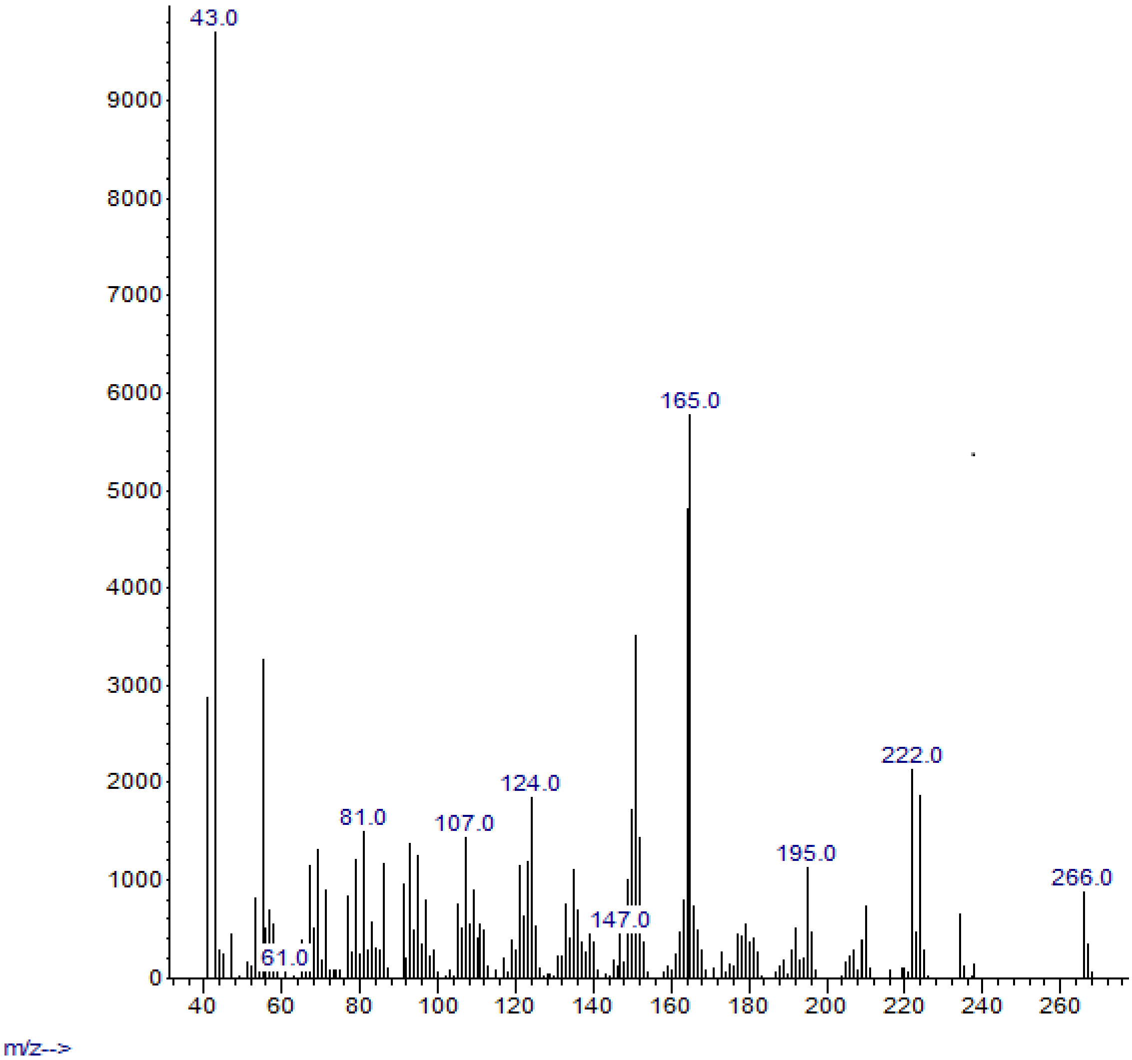

Figure 11. Chromatogram of Silver Nanoparticle.

4. CONCLUSION

This study successfully demonstrated the green synthesis of silver nanoparticles using aqueous extracts of elephant grass, unripe plantain peel, and bambara groundnut shell. All three biomass types were effective, with elephant grass producing the smallest and most uniform nanoparticles and the highest stability. The findings confirm that underutilized plant residues can serve as sustainable feedstocks for nanomaterial production, with potential applications in antimicrobial coatings, water treatment, and catalysis. Future work will focus on scaling up the synthesis and testing functional performance in real-world application.

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Conflicts of Interest

We declare that there is no conflict of interest concerning this publication.

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