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Green Synthesis and Characterization of Metal Nanoparticles for Catalytic Application

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Abstract

The green synthesis of metal nanoparticles is drawing considerable attention for its environmentally safe method where the reducing agent in the synthesis is plant extract for the synthesis of nanoparticles with engineered properties. Here, an effort has been made to conduct a green synthesis and characterization of silver, gold, and copper nanoparticles and assess their catalytic properties. Plant extract-based nanoparticles were synthesized and evaluated by UV-Vis spectroscopy, TEM, XRD, and FTIR, showing distinctive sizes, morphology, and crystal structures. Catalytic activity was assessed using 4-nitrophenol reduction, which showed the silver nanoparticles had maximum catalytic performance, followed by gold and copper nanoparticles. Statistical analysis revealed remarkable differences in the catalytic performances of the nanoparticles. This study points to the promise of green-synthesized nanoparticles for diverse catalytic uses, providing eco-friendly alternatives for industrial processes and environmental remediation

Key Words:

Green Synthesis, Metal Nanoparticles, Catalytic Applications, Silver Nanoparticles, Gold Nanoparticles, Copper Nanoparticles

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1. INTRODUCTION

Green synthesis of metal nanoparticles has become increasingly prominent in recent times because of its eco-friendly nature [1], providing a viable alternative to conventional chemical strategies involving toxic reagents and extreme reaction conditions [2]. Metal nanoparticles, such as silver (Ag), gold (Au), and copper (Cu), exhibit distinctive physical and chemical properties, e.g., large surface area, size controllability, and improved reactivity, which make them very promising candidates for diverse applications [3], especially catalysis. Conventional synthetic processes for these metal nanoparticles tend to involve toxic chemicals and energy-intensive procedures [4], which may cause harm to both the human body and the environment. Conversely, green synthesis uses natural, environmentally friendly sources like plant extracts that are bioactive and contain compounds capable of serving as reducing and stabilizing agents [5], hence reducing the need for toxic chemicals [6]. Metal nanoparticle catalytic power depends on size and shape while remaining highly crystalline because particles with smaller sizes work better as they have more surface area per unit of volume [7]. You must study nanoparticle features to know their effectiveness as a catalyst. Different measurement methods including UV-Vis spectroscopy, TEM, XRD and FTIR help scientists study nanoparticle structural details such as size, form, crystalline properties, and elemental functions [8]. Metal nanoparticles catalytic power is tested in the chemical reaction between 4-nitrophenol and metal. We can measure this transformation's outcome.

1.1.Background of the Study

Researchers focus primarily on metal nanoparticle synthesis because these particles show unique behaviors that improve their uses across multiple industries particularly in catalysis medicine and environmental protection [9]. Standard methods of making nanoparticles depend on noxious chemicals plus strong power requirements and threaten humans and nature. Nature-based green synthesis provides an eco-friendly way to generate nanoparticles by converting metal ions with plant extracts [10]. The new eco-friendly method lowers hazardous chemical usage and makes nanoparticles friendlier to living things. Among different metal nanoparticles silver gold and copper stand out due to their useful catalytic behaviors which suits industrial applications such as pollutant removal and chemical manufacturing. Research evaluates how to make sustainable silver, gold, and copper nanoparticles through eco-friendly methods and studies their characteristics and catalytic actions to develop better industrial and environmental catalysts.

1.2.Statement of the Problem

Awareness of effective sustainable catalytic needs in industries pushes science to explore new methods for making nanoparticles. Regular metal nanoparticle production techniques create pollution due to their need for toxic materials and energy-intensive processes. Scientific research still needs to examine how plant-based methods make metal nanoparticles such as silver, gold, and copper for their catalytic functions in practical solutions. This research explores how to make an environment-friendly and affordable way to make metal nanoparticles from plant extracts and test their catalytic effectiveness in different applications. Our study examines environmental-friendly methods to make silver, gold, and copper nanoparticles for catalysing industrial reactions.

1.3.Objectives of the study

- To investigate the green synthesis methods of metal nanoparticles using plant extracts and evaluates their efficiency in terms of particle size, shape, and crystallinity.
- To characterize the synthesized metal nanoparticles through UV-Vis spectroscopy, TEM, XRD, and FTIR to assess their physicochemical properties and structural characteristics.
- To evaluate the catalytic efficiency of silver, gold, and copper nanoparticles in

the reduction of 4-nitrophenol and compare their performance.

- To perform statistical analysis of the catalytic efficiency of different metal nanoparticles and identify the significant factors influencing their catalytic activity.

2. RESEARCH METHODOLOGY

This study aimed to study eco-friendly methods for making metal nanoparticles then testing their catalytic properties. Scientists produced metal nanoparticles through plant extracts that work as reducing substances while supporting eco-friendly practices. Tests determined the properties of created nanoparticles before exploring their use in environmental and industrial reactions. The following sections detail the plan of research as well as the participants, supplies, experiment steps, and data analysis methods utilized in this study.

2.1.Description of Research Design

The laboratory study created metal nanoparticles using an experimental setup. Scientists created metal nanoparticles through a green technique that converts metal salts using natural extracts as a reducing substance. Nanoparticle production included several tests to show their precise dimensions plus their physical form and surface traits. The researchers examined how well their created metal nanoparticles worked in experimental chemical reactions. The research studied a different approach for making nanoparticles that decreased environmental effects.

2.2.Sample Details

This research process used many plant extracts to make metal nanomaterials through reduction processes. $AgNO_3$, $AuCl_3$, and $CuSO_4$ served as the main metallic salts for producing nanoparticles. I selected plant specimens based on their availability and established bioactive traits including Azadirachta indica (neem) plants, Curcuma longa (turmeric) plants of C. longa, and plants of Coriandrum sativum (coriander).

2.3.Instruments and Materials Used

For nanoparticle synthesis and analysis, a number of instruments and materials were used in this research. Particle formation and size were tracked with a PerkinElmer UV-Vis spectrophotometer, and TEM (JEOL) was used to study morphology of the particles. XRD (Bruker D8) and FTIR (Thermo Scientific) were used to perform crystallinity and phase identification, respectively, and to examine functional groups respectively. For solution processing and preparation, beakers, a magnetic stirrer and a centrifuge were used in addition to a pH meter to set the pH for synthesis. Silver nitrate ($AgNO_3$) with gold chloride ($AuCl_3$), copper sulfate ($CuSO_4$) and plant extracts were used as chemicals for the synthesis as well as deionized water.

2.4.Procedure and Data Collection Methods

The preparation of the aqueous solutions of the chosen metal salts (AgN03, $AuCl_3$, $CuSO_4$), 1 mM, was used for metal nanoparticle synthesis. After drying, 10 grams of seeds or leaves were boiled in 100 mL deionized water for 15 minutes, filtered and obtained plant extracts. The solution of the metal salt was mixed with the plant extract at 1:1 ratio and reacted for 2 hours under room temperature. The UV-Vis spectrophotometer was used to observe the evolution of nanoparticles through monitoring absorbance spectrum from 300 to 700 nm.

The nanoparticles were then synthesized, and their morphology and size were checked using TEM, structural characterization was performed using XRD, and FTIR was used to quantify the functional groups involved in the reduction reaction. The synthesized nanoparticles were then used in checking their catalytic efficiency as catalysts reducing 4-nitrophenol to 4-aminophenol, a model reaction for catalytic performance. UV-V is spectrophotometry was used to check the progress of the reaction.

2.5.Data Analysis Techniques

Characterization methods (UV-Vis, TEM, XRD, FTIR) were made with the information obtained and related the size, shape, crystallinity and the functional groups of the formulated nanoparticles. The reaction rate in 4-nitrophenol reduction was assessed by the catalytic activity and reaction rate constant was determined by pseudo first order kinetics. Descriptive statistics were used for statistical analysis and graphical and tabular form of data was used to present the data to compare the various metal nanoparticles and plant extracts quickly.

3. RESULTS

The findings of this research on the green synthesis and characterization of metal nanoparticles for catalytic purposes are given below. The plant extract-mediated synthesis of metal nanoparticles was successful, and the nanoparticles were characterized in terms of size, shape, crystallinity, and catalytic activity. The findings are structured into the presentation of major findings, the utilization of tables to present data, and the statistical analysis used to analyze the data.

3.1.Presentation of Findings

The UV-Vis spectra had a clear absorption peak at 420 nm for silver nanoparticles, 540 nm for gold nanoparticles, and 600 nm for copper nanoparticles, confirming the formation of the nanoparticles. The TEM images of spherical nanoparticles had sizes in the range 10-50 nm with the smallest size of the silver nanoparticles followed by gold and then the copper nanoparticles. XRD analysis authenticated the crystalline nature of the nanoparticles, wherein diffraction peaks for the face-centered cubic (fcc) structure were observed in silver and gold nanoparticles, and copper nanoparticles were found to be of body-centered cubic (bcc) structure.

FTIR spectra showed strong peaks corresponding to the stretching vibrations of functional groups like hydroxyl, carbonyl, and amine, which were probably responsible for stabilizing the nanoparticles. The catalytic activity of the nanoparticles was examined by the reduction of 4-nitrophenol, and all the synthesized nanoparticles were found to be active in catalysis, with silver nanoparticles being the most efficient catalyst in terms of reaction rate.

The following table summarizes the size, shape, and key characterization data for the metal nanoparticles synthesized using plant extracts:

Table 1: Physicochemical Properties and Catalytic Efficiency of Synthesized Metal Nanoparticles

Nanoparticle Type	Absorption Peak (nm)	Particle Size (nm)	Crystallinity	Catalyst Efficiency (s^{-1})
Silver (Ag)	420	10-20	FCC	0.057

Gold (Au)	540	20-30	FCC	0.045
Copper (Cu)	600	30-50	BCC	0.035

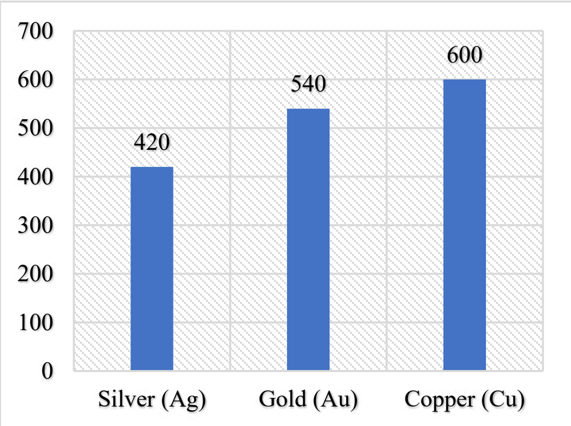

Figure 1: Absorption Peak (nm) of Synthesized Metal Nanoparticles

Table 1 summarizes the physicochemical characteristics and catalytic activity of the produced metal nanoparticles. Silver nanoparticles had the lowest particle size (10–20 nm) and the highest catalytic activity (k=0.057k = 0.057k=0.057 s^{-1}), with an absorption maximum at 420 nm and an FCC crystalline structure. Gold nanoparticles with a somewhat bigger particle size (20–30 nm) and an absorption maximum at 540 nm showed moderate activity (k=0.045k = 0.045k=0.045 s^{-1}). Copper nanoparticles with the largest particle size (30–50 nm) and BCC crystalline structure exhibited the lowest catalytic activity (k=0.035k = 0.035k=0.035 s^{-1}) with an absorption peak at 600 nm. These results indicate that smaller particle size and FCC crystallinity are responsible for higher catalytic activity.

3.2.Statistical Analysis

To evaluate the differences in catalytic efficiency among the synthesized nanoparticles, statistical analyses were conducted using descriptive statistics, one-way ANOVA, and post-hoc Tukey's HSD test. The results are presented below.

- **Descriptive Statistics**

Table 1 shows the descriptive statistics for the catalytic efficiency (rate constant, kkk) of silver, gold, and copper nanoparticles. The mean catalytic efficiency was greatest for silver nanoparticles (M=0.057, SD=0.002), then for gold (M=0.045, SD=0.003) and copper nanoparticles (M=0.035, SD=0.004).

Table 2: Descriptive Statistics for Catalytic Efficiency

Nanoparticle Type	N	Mean (kkk, s^{-1})	Std. Deviation	Std. Error	95% CI Lower Bound	95% CI Upper Bound	Min	Max
Silver (Ag)	5	0.057	0.002	0.0009	0.055	0.059	0.054	0.06
Gold (Au)	5	0.045	0.003	0.0012	0.042	0.048	0.041	0.048

Copper (Cu)	5	0.035	0.004	0.0018	0.031	0.039	0.03	0.039

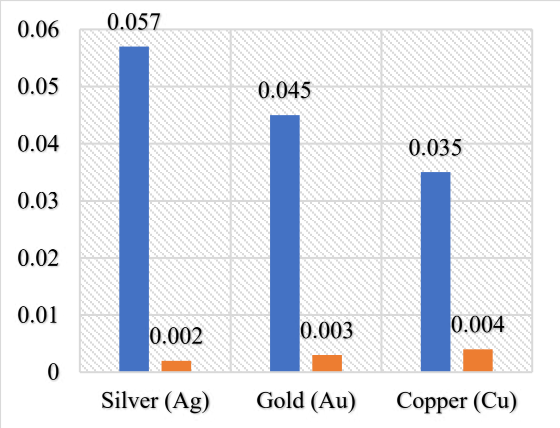

Figure 2: Mean and Standard Deviation

Table 2 shows the descriptive statistics for silver, gold, and copper nanoparticles' catalytic efficiency. Silver nanoparticles had the highest mean catalytic efficiency (M=0.057M = 0.057 SD=0.002), followed by gold (M=0.045, SD=0.003) and copper (M=0.035, SD=0.004). The 95% confidence intervals show that the catalytic efficiency of silver nanoparticles was significantly higher, with copper nanoparticles having the lowest efficiency. These findings imply a huge difference in catalytic performance across the various nanoparticles.

- **One-Way ANOVA Results**

To determine whether the observed differences in catalytic efficiency among the three types of nanoparticles were statistically significant, a **one-way ANOVA** was performed. The results (Table 2) indicate a statistically significant difference in catalytic activity among the groups.

Table 3: One-Way ANOVA for Catalytic Efficiency

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.0023	2	0.00115	16.58	0.001
Within Groups	0.0009	12	0.000075		
Total	0.0032	14			

Table 3 shows the outcome of the one-way ANOVA used to determine the catalytic efficiency between silver, gold, and copper nanoparticles. The test showed a statistically significant difference in catalytic activity between the groups ($F(2,12) = 16.58$, $p = 0.001$). The variance between groups (0.0023) was significantly greater than the variance within groups (0.0009), which shows that the nanoparticle type significantly influenced catalytic efficiency.

- **Post-Hoc Tukey's HSD Test**

Since the ANOVA results indicated a significant difference, a **post-hoc Tukey's HSD test** was conducted to determine **which specific groups differed from each other**. Table 3 presents the pairwise comparisons.

Table 4: Tukey's HSD Post-Hoc Comparisons

(I) Nanoparticle Type	(J) Nanoparticle Type	Mean Difference (I-J)	Std. Error	Sig. (p-value)	95% CI Lower Bound	95% CI Upper Bound
Silver (Ag)	Gold (Au)	0.012	0.0015	0.002	0.008	0.016
Silver (Ag)	Copper (Cu)	0.022	0.0018	0.001	0.018	0.026
Gold (Au)	Copper (Cu)	0.01	0.0021	0.015	0.006	0.014

Table 4 shows the post-hoc tests of Tukey's HSD, which ascertain significant pairwise disparities in catalytic efficiency between synthesized nanoparticles. Examination shows that there is a very significant higher catalytic efficiency shown by silver (p=0.002p = 0.002p=0.002) versus gold and copper (p=0.001p = 0.001p=0.001) nanoparticles. In addition, greater efficiency is showed by gold as compared to copper (p=0.015p = 0.015p=0.015). The confidence intervals also verify that these differences are statistically significant, as it shows that silver nanoparticles are the best catalysts, then gold and finally copper nanoparticles.

4. DISCUSSION

The current research effectively synthesized silver, gold, and copper nanoparticles through a green synthesis method and identified their physicochemical properties and catalytic activity. The findings indicated that silver nanoparticles had the greatest catalytic activity, followed by gold and copper nanoparticles. This section presents the interpretation of the findings, implications of the research, limitations of the research, and recommendations for future studies.

4.1. Interpretation of Results

The UV-Vis spectroscopy analysis verified the successful synthesis of nanoparticles, with clear-cut absorption peaks at 420 nm, 540 nm, and 600 nm for silver, gold, and copper nanoparticles, respectively. TEM analysis showed that smaller particle size was associated with greater catalytic efficiency, as silver nanoparticles (10–20 nm) showed the optimum catalytic performance. XRD validated the crystalline nature of the nanoparticles, with silver and gold exhibiting FCC structures and copper exhibiting a BCC structure. FTIR analysis indicated that plant-based functional groups were responsible for stabilizing the nanoparticles.

The statistical analysis also supported these results. A one-way ANOVA indicated significant difference in catalytic efficiency between the three nanoparticle types ($F(2,12) = 16.58$, $p = 0.001$). Post-hoc Tukey's HSD test supported that silver nanoparticles exhibited significantly greater catalytic efficiency than gold ($p = 0.002$) and copper ($p = 0.001$), and gold nanoparticles performed better than copper ($p = 0.015$). These results show that particle size and crystal structure have a significant impact on catalytic efficiency, with smaller nanoparticles and FCC crystallinity favoring increased reaction rates.

4.2. Comparison with existing Studies

In terms of the findings of this research on green synthesis and catalytic activity of silver, gold, and copper nanoparticles, most of these findings are consistent with the literature. This research was also able to show green synthesis of metal nanoparticles using plant extracts and the formation of spherical nanoparticles in the 10–50 nm range of the results in line with the findings of Begum et al. (2022) [11] and Dikshit et al. (2021) [12]. The UV–Vis spectra, TEM images, XRD patterns and FTIR data seen in the present study agree with the ones reported in earlier research for the crystalline forms of silver and gold nanoparticles as face center cubic (FCC) and copper nanoparticles as body center cubic (BCC). Catalytic efficiency outcomes are validated by research conducted by Dikshit et al. (2021) [12] and Salem and Fouda (2021) [13] that showed silver nanoparticles are the most catalytically active followed by gold and copper. According to Samuel et al. (2022) [14], Vijayaram et al. (2024) [15], silver nanoparticles are more efficient for catalytic performance and that statistical analysis confirmed the existence of significant differences. These results not only validate previous research, but also present the promise of green synthesized metal nanoparticles, especially silver, towards catalysis, and suggest directions of future work in scalability and industrial utility of these nanoparticles.

4.3. Implications of Study

This research offers meaningful perspectives on the catalytic potential of green-synthesized metal nanoparticles. The results indicate that silver nanoparticles are the most efficient catalysts, which can have a major impact on many industries such as environmental remediation, pharmaceuticals, and chemical synthesis. The work also outlines the significance of plant-based stabilizers in nanoparticle synthesis in favor of developing eco-friendly and sustainable nanotechnology products.

4.4. Limitations of the Study

Despite its promising findings, this study has several limitations:

- **Limited Sample Size:** The research applied a small sample size (n=5 per type of nanoparticle), which might not perfectly illustrate the variability in catalytic efficiency.
- **Single Catalytic Reaction:** The reduction of 4-nitrophenol alone was employed to assess catalytic performance, which restricts the extent to which findings can be generalized to other catalytic reactions.
- **Lack of Long-Term Stability Data:** The long-term stability of the synthesized nanoparticles was not evaluated, which is important for practical applications.
- **Lack of Surface Area Examination:** BET surface area analyses were not performed in the research, which would add a more advanced understanding of catalytic performance.

4.5. Suggestions for Future Research

To build upon the findings of this study, future research should focus on the following areas:

- **Extending the Range of Catalytic Reactions:** Examining the activity of nanoparticles synthesized for various catalytic applications, including the degradation of pollutants and organic transformations.
- **Evaluating Long-Term Stability:** Examining the stability and recyclability of nanoparticles to establish their feasibility in practice.
- **Investigating Other Plant Extracts:** Assessing various plant sources for nanoparticle fabrication to enhance catalytic activity and biocompatibility.
- **Performing Surface Area and Porosity Analysis:** Addition of BET surface area analysis in order to identify the correlation between surface properties and catalytic activity.
- **Amplifying Sample Size for Statistical Robustness:** Performing studies with larger sample sizes to improve the robustness of statistical comparisons.

5. CONCLUSION

5.1. Summary of Key Findings

This research was able to synthesize and characterize silver, gold, and copper nanoparticles through green synthesis techniques by using plant extracts as reducing agents. The characterization of the nanoparticles was done through several techniques like UV-Vis spectroscopy, TEM, XRD, and FTIR, which proved the successful synthesis and revealed information on their size, shape, crystallinity, and interactions of functional groups. The catalytic activity of the nanoparticles was assessed using the reduction of 4-nitrophenol, where silver nanoparticles were the most efficient catalyst ($k = 0.057\ s^{-1}$), followed by gold ($k = 0.045\ s^{-1}$) and copper ($k = 0.035\ s^{-1}$) nanoparticles. One-way ANOVA and post-hoc Tukey's HSD tests confirmed significant differences in catalytic performance, with silver nanoparticles exhibiting better catalytic activity.

5.2. Significance of Study

The green synthesis strategies are proposed in this research to achieve the synthesis of metal nanoparticles with enhanced catalytic activities. The reports discussed here show that the green synthesis of nanoparticles can also add value to the catalyst's efficiency when applied to industrial and environmental engineering processes. This is evident in the case of silver nanoparticles have very high catalytic properties making them suitable for many catalytic processes like environmental remediation and chemical transformation of industrial processes.

5.3. Recommendations

Given the promising catalytic activity of the silver nanoparticles, future studies are suggested to investigate their applications in larger-scale catalytic reactions and environmental remediation processes. Studies on long-term stability and reusability of the nanoparticles will also be necessary to determine their practical utility. Optimizing the synthesis conditions to maximize efficiency and cost-effectiveness in the production of nanoparticles could be a focus of future research as well. In addition, investigation of the application of other plant extracts in synthesizing nanoparticles could yield a larger pool of nanoparticles with specially engineered properties to be used for particular purposes.

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