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Gold Nanoparticle Synthesis Using Quercetin: Innovation in Biopreneur

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ABSTRACT

Biosynthesis offers an environmentally friendly approach for manufacturing nanoparticles, with flavonoids such as quercetin showing potential as reducing agents. **This study aimed** to synthesize gold nanoparticles (AuNPs) from $HAuCl_4$ using quercetin as a reducing agent. **The synthesis process** was monitored using UV-Vis spectrophotometry, and the particle size and stability of the nanoparticles were characterized using a Particle Size Analyzer (PSA). **The synthesized AuNPs exhibited** a color change from light yellow to deep purple, with a peak absorbance between 500-600 nm. The average particle size was found to be 116.7 nm, with a zeta potential of -12.2 mV, and a polydispersity index of 0.293. The inhibitory activity of the AuNPs was assessed by their effect on the tyrosinase enzyme, yielding an IC_{50} value of 970 µg/mL. **These results suggest** that gold nanoparticles synthesized using quercetin are stable and exhibit potential inhibitory activity against tyrosinase. The study concludes that this green synthesis method has the potential for further development in drug delivery systems, providing an innovative approach in biopreneurship.

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1. INTRODUCTION

Nanotechnology has seen rapid advancements in recent decades, particularly in drug delivery systems. This is due to its ability to enhance solubility, absorption, bioavailability, and controlled drug release [1]. By definition, nanotechnology involves manipulating matter at the nanoscale, typically ranging from 1 to 1000 nanometers [2, 3]. This technology can be applied in various fields, including optics, electronics, biomedical sciences, drug delivery systems, and the chemical industry [4]. One notable development in nanotechnology is the use of gold nanoparticles (AuNPs).

In this study, the synthesis of gold nanoparticles using quercetin as a reducing agent exemplifies a sustainable approach to nanotechnology. This aligns with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly SDG 9: Industry, Innovation, and Infrastructure, by promoting innovation in the field of biopreneurship. The environmentally friendly biosynthesis process, utilizing natural

compounds like quercetin, also contributes to SDG 12: Responsible Consumption and Production, as it avoids the use of toxic chemicals and reduces environmental impact. Furthermore, the potential applications of these gold nanoparticles in drug delivery systems could advance healthcare technologies, thus supporting SDG 3: Good Health and Well-being by providing novel solutions for disease treatment. Through such innovations, this research demonstrates how scientific advancements can contribute to the achievement of broader global sustainability goals.

AuNPs have gained attention due to their unique characteristics, ease of synthesis, and controllable particle size [5]. Their benefits, such as biocompatibility, unique optical properties, and readily modifiable surface chemistry, have made AuNPs highly desirable. Consequently, AuNPs are widely used as drug-delivery systems for various diseases [6]. Moreover, its unique physicochemical properties, including its inert and non-toxic nature, make it an effective delivery system for pharmaceuticals. It can deliver drugs, recombinant proteins, and vaccines to their targets while also controlling drug release [7, 8].

Nanoparticles are produced using two primary methods: top-down and bottom-up. The top-down approach, a physical method, has drawbacks such as surface structural defects, lengthy synthesis times, and demanding high energy and spacious space [4]. The bottom-up approach, a chemical method, often involves metal reduction using stabilizers, which can be toxic and limit its use in medical research [9]. To address the challenges associated with traditional nanoparticle synthesis methods, green synthesis has emerged as a promising alternative. Biosynthesis utilizes biological agents like bacteria, fungi, and plants to synthesize nanoparticles [4]. This approach offers several advantages, including environmental friendliness, affordability, scalability, and the elimination of the need for high-pressure, energy, temperature, and toxic chemicals [9]. One application of biosynthesis involves using flavonoid compounds as reducing agents. Flavonoids are chosen for their reducing properties, which facilitate the formation of AuNPs [10].

Flavonoids, a class of polyphenols, have been extensively studied for their significant pharmacological activities. 3,3', 4', 5,7 pentahydroxyflavone, one example of a flavonoid is Quercetin. A flavonol compound derived from the Latin word "Quercetum" meaning oak forest and this compound cannot be produced by the human body. [11] Quercetin effectively inhibits both monophenolase and diphenolase tyrosinase activities. Additionally, it competitively and reversibly inhibits the formation of dopaquinone [12]. Previous research has explored the synthesis of gold nanoparticles using quercetin [13]. Moreover, employing quercetin as a capping agent in gold nanoparticle synthesis has demonstrated its cost-effectiveness [14].

This research aimed to synthesize gold nanoparticles using quercetin as a reducing agent. The synthesized gold nanoparticles were characterized using UV-Vis spectrophotometry and a Particle Size Analyzer (PSA). The inhibitory activity of the synthesized gold nanoparticles on tyrosinase was also evaluated.

2. RESEARCH METHOD

2.1. Materials

Quercetin (Sigma-Aldrich), Au foil 24-carat purity 99.99% (PT. Antam, Indonesia), L-Tyrosine substrate (Sigma-Aldrich), Tyrosinase enzyme (Sigma-Aldrich), Kojic Acid (spectrum), aqua pro injection (Otsuka, Japan), HNO3 65%, HCl 37%, Potassium Dihydrogen Phosphate/KH2PO4 (Merck), Sodium Hydroxide (NaOH) (Merck), and Dimethyl Sulfoxide/DMSO (Vivantis).

2.2. Methods

2.2.1. Preparation of HAuCl4 0.002 M Solutions

Au foil 120 mg was dissolved in 30 mL hot aqua regia that was prepared by mixing HNO3 and HCl in a ratio of 1:3 at $100°C$, and 60 mL of aqua pro injection will be added three times. The final solution will be added with 0.01 MHCl solution up to 300 mL to reach a 0.002 M $HAuCl_4$ solution [15].

2.2.2. Preparation of HAuCl4 0.002 M with Gummy Arabic Solutions

Gum Arabic was dissolved in 250 mL of sterile water (aqua pro injection) with stirring at 1000 rpm at a temperature of $100°C$. Subsequently, 205 mL of the gum Arabic solution was combined with 7.5 mL of sterile water, heated to $55°C$, and stirred at 1000 rpm. $HAuCl_4$ solution was then added to the gum Arabic solution while stirring at 1000 rpm. UV-Vis absorption spectra were recorded immediately after the preparation.

2.2.3. Biosynthesis of Gold Nanoparticles

AuNPs were synthesized according to the procedure outlined in our previous study. The biosynthesis of gold nanoparticles using quercetin as a reducing agent was conducted with varying concentrations of

quercetin solution (2 mM; 4 mM; 8 mM) and $HAuCl_4$ solution (Table 1) quercetin. The formation of gold nanoparticles was confirmed by measuring their maximum wavelength using a UV-Vis spectrophotometer.

Table 1. Variation of Biosynthesis Gold Nanoparticles Formula

Formula	$HAuCl_4$	**Quercetin**
F1	$HAuCl_4$ 0.002 M + Gum Arabic	2 mM
F2	$HAuCl_4$ 0.002 M + Gum Arabic	4 mM
F3	$HAuCl_4$ 0.002 M + Gum Arabic	8 mM
F4	$HAuCl_4$ 0.002 M	2 mM
F5	$HAuCl_4$ 0.002 M	4 mM
F6	$HAuCl_4$ 0.002 M	8 mM

Table 1 outlines the different formulations used for the biosynthesis of gold nanoparticles (AuNPs) in this study, utilizing varying concentrations of quercetin (2 mM, 4 mM, 8 mM) combined with $HAuCl_4$ solutions. These formulations were designed to explore the influence of quercetin concentration on the properties of the synthesized nanoparticles, such as their size, stability, and potential for drug delivery applications. The varying concentrations of quercetin serve to evaluate how the reducing agent affects the overall synthesis process, particularly in terms of nanoparticle formation and characteristics, as confirmed by UV-Vis spectrophotometry.

2.2.4. Stability study and characterization of Gold nanoparticles

The stability of the gold nanoparticles was assessed over eight weeks (two months) using a UV-visible spectrophotometer (TECAN, Switzerland) at a wavelength of 400-700 nm. The stability was determined by monitoring any changes in the ruby red colour of the nanoparticles, which is reflected in their absorbance.The optimal gold nanoparticle formulation was characterized using a PSA model HORIBA SZ-100 (HORIBA Ltd, Kyoto, Japan). This instrument was used to determine the characteristics of the gold nanoparticles, including particle size, polydispersity index, and zeta potential.

2.2.5. Tyrosinase assay of Gold Nanoparticles

The optimal quercetin gold nanoparticle formulation was selected. Serial dilutions were performed using 50 mM phosphate buffer at pH 6.5 to obtain a series of concentrations ranging from 9457 to 18.470 µg/mL. Kojic acid, used as a standard, was also dissolved in 50 mM phosphate buffer at pH 6.5 to create a series of concentrations ranging from 500 to 7.8125 µg/mL. Both the gold nanoparticles and kojic acid were tested for their tyrosinase inhibitory activity, and the absorbance was measured at a wavelength of 480 nm [16]. The percentage (%) of tyrosinase inhibitory activity was calculated using Equation 1 [17]:

$$\text{Percentage Inhibition} = \left(\frac{A-B}{A}\right) \times 100\% \tag{1}$$

Note:

- A = Blank Absorbance
- B = Sample Absorbance

The IC_{50} value is calculated using Equation 2, where the x-axis shows the concentration, the y-axis shows the percentage (%) of inhibition, and the values of a, b, and R2 are generated. A and b are entered into equation 2, and the IC_{50} value is obtained from x after replacing y with 50 [18].

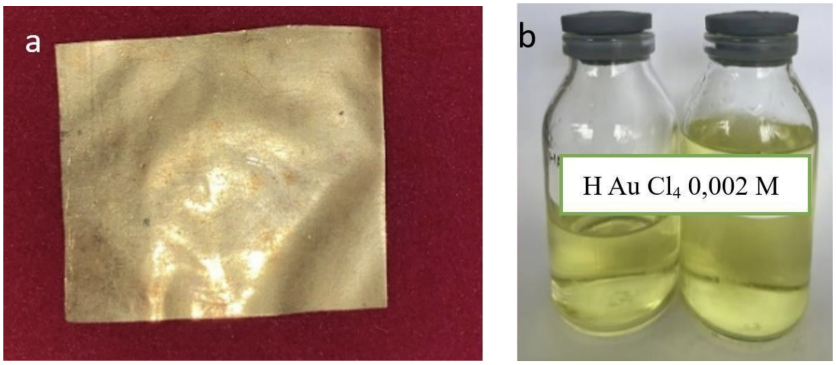
$$y = a + b\ln(x) \tag{2}$$

The IC_{50} calculation is crucial in determining the inhibition potency of the synthesized gold nanoparticles. The IC_{50} value represents the concentration at which 50% of the enzyme activity is inhibited, indicating the effectiveness of the nanoparticles in reducing tyrosinase enzyme activity. A lower IC_{50} value corresponds to a stronger inhibitory effect of the nanoparticles. Therefore, IC_{50} testing is essential in evaluating the therapeutic potential of gold nanoparticles used in drug delivery systems and other biomedical applications. The IC_{50} results provide a clearer understanding of the quality and effectiveness of gold nanoparticles in addressing conditions associated with tyrosinase activity.

3. RESULT AND DISCUSSION

3.1. Preparation HAuCl4 0.002 M Solutions

This study utilized gold foil (Figure 1a) to prepare a 0.002 M $HAuCl_4$ solution (Figure 1b). The $HAuCl_4$ solution was synthesized from gold foil using aqua regia. The conversion of gold foil (Au0) to $AuCl_4$ was accompanied by a distinct change in the solution appearance. Since no Nitrogen Oxide (NO) gas was produced, 60 mL of sterile water (aqua pro injection) was required [19].



(a) Au Foil (b) $HAuCl_4$ 0.002 M Solutions

Figure 1. Preparation $HAuCl_4$ 0.002 M Solutions

The solution was supplemented with 0.01 M HCl to prepare a 0.002 M $HAuCl_4$ solution [20]. UV-visible absorption spectroscopy is a commonly used technique for analyzing the quantum optical properties of $HAuCl_4$ [21]. The $HAuCl_4$ 0.002 M solution was confirmed to have its maximum wavelength at 310 nm, as shown in Figure 2.

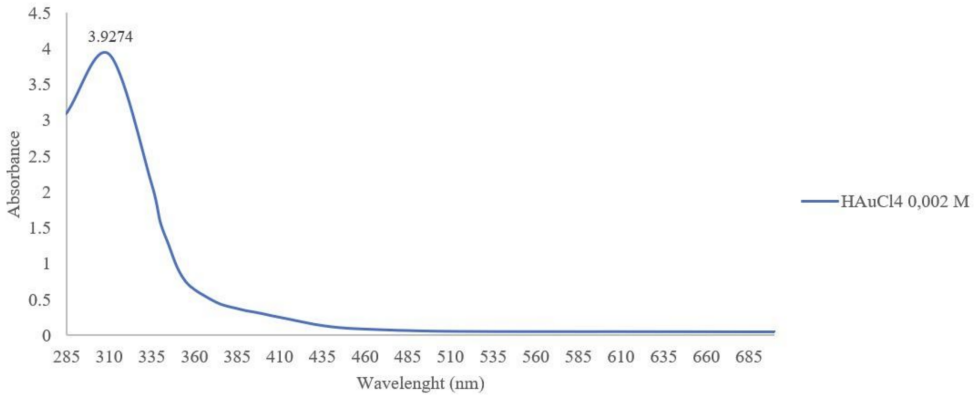
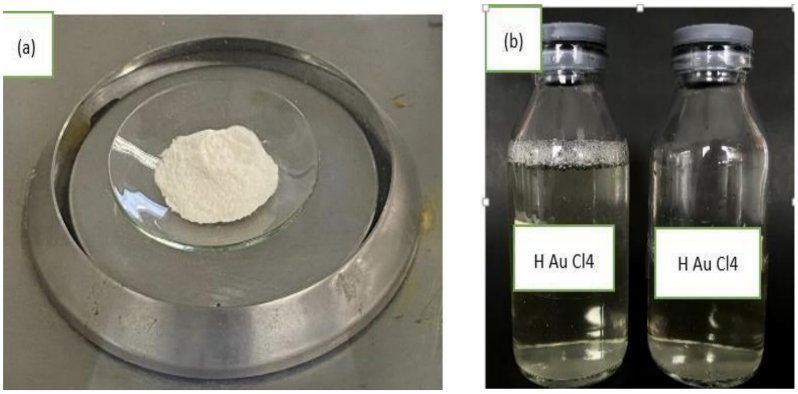


Figure 2. Maximum Wavelength and Absorbance of $HAuCl_4$ 0.002 M Solution

Figure 2 show the maximum wavelength and absorbance of the $HAuCl_4$ 0.002 M solution, which was confirmed at 310 nm using UV-Vis spectrophotometry. This absorption spectrum is essential for understanding the quantum optical properties of $HAuCl_4$, providing insight into the characteristics of the solution before it undergoes the nanoparticle synthesis process. The specific wavelength of 310 nm indicates the presence of $HAuCl_4$, and its stability at this wavelength serves as a baseline for monitoring the subsequent formation of gold nanoparticles in the following steps of the experiment.

3.2. Preparation of HAuCl4 0.002 M with Gummy Arabic Solutions

The $HAuCl_4$ 0.002 M solution was combined with gum Arabic to form a $HAuCl_4$ 0.002 M solution + gum Arabic mixture (Figure 3). The $HAuCl_4$ 0.002 M solution + gum Arabic mixture was then analyzed for its maximum wavelength, which was found to be at 310 nm (Figure 4).



(a) Gummy Arabic (b) $HAuCl_4$ 0.002 M + Gummy Arabic Solutions

Figure 3. Preparation of $HAuCl_4$ 0.002 M with Gummy Arabic Solutions

The $HAuCl_4$ 0.002 M solution was combined with gum Arabic, a non-toxic, hydrophilic phytochemical glycoprotein polymer commonly used as a stabilizer in the food and pharmaceutical industries [22]. Previous studies have demonstrated gum Arabic ability to stabilize gold nanoparticle solutions [23]. The $HAuCl_4$ 0.002 M + gum Arabic solutions exhibited their highest absorbance peak at 310 nm.

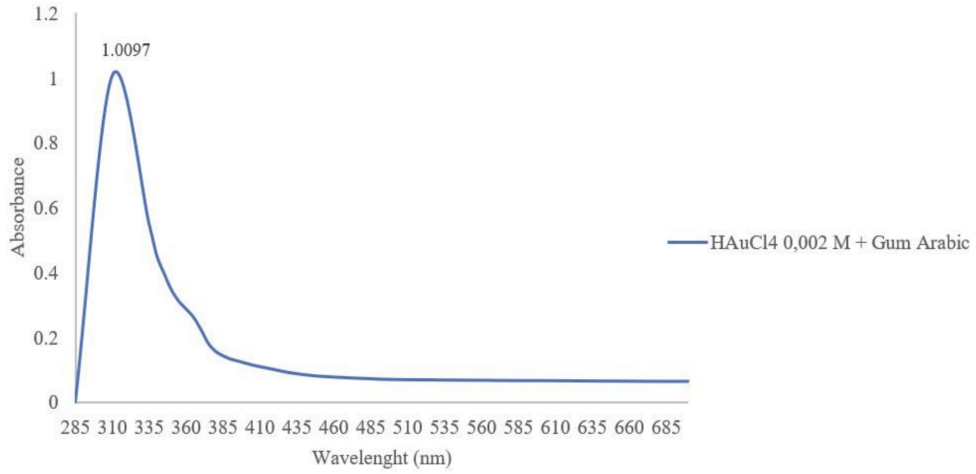


Figure 4. Wavelength curve $HAuCl_4$ 0.002 M with Gummy Arabic Solutions

Figure 4 presents the wavelength curve of the $HAuCl_4$ 0.002 M solution combined with gum Arabic. The absorption peak at 310 nm indicates the effective stabilization of the gold chloride solution by gum Arabic, a natural stabilizer known for its non-toxic properties. This stabilization ensures that the gold ions remain dispersed in solution, preventing aggregation and facilitating the subsequent formation of gold nanoparticles. The observed peak confirms the successful integration of gum Arabic into the solution, making it a suitable candidate for further nanoparticle biosynthesis processes.

3.3. Biosynthesis of Gold Nanoparticles

The formula used a $HAuCl_4$ 0.002 M solution gum arabic (F1–F3) and a $HAuCl_4$ 0.002 M solution (F4–F6). $HAuCl_4$ solutions and $HAuCl_4$ 0.002 M solution + gum arabic will be synthesized using quercetin solution (DMSO + aqua pro injection) with various concentrations of 2 mM, 4 mM, and 8 mM. The results of each formula (F1-F6) can be seen in Figure 5. The $HAuCl_4$ solution could be completely reduced to form

gold nanoparticles of formula 1 (F1), which was confirmed by the fact that there was no further change in the UV-vis spectrum after quercetin was added to the prepared gold solution [24].

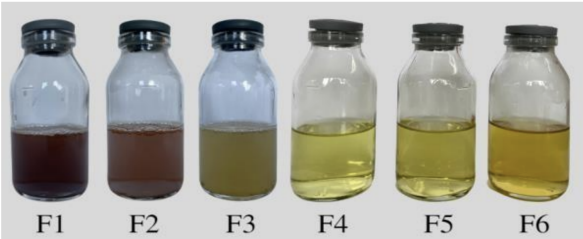


Figure 5. Biosynthesis of Gold Nanoparticles

Nanoparticle biosynthesis was conducted using a quercetin solution prepared in DMSO and aqua pro injection at $40°C$ with 1000 rpm stirring for 90 minutes. Quercetin exhibits high solubility in DMSO, reaching 150 µg/mL [25]. Aqua pro injection is sterile water free from microbes and other additives [26]. Its use as a solvent minimizes the presence of other substances, including microbes, which can act as reducing agents [27, 28].

The observed colour change is a characteristic of the Surface Plasmon Resonance (SPR) of the formed gold nanoparticles. UV-vis spectroscopy is a crucial tool for confirming the formation and stability of gold nanoparticles in solution. Figure 6 illustrates the UV spectra of the various Au NP formulations (F1-F6).

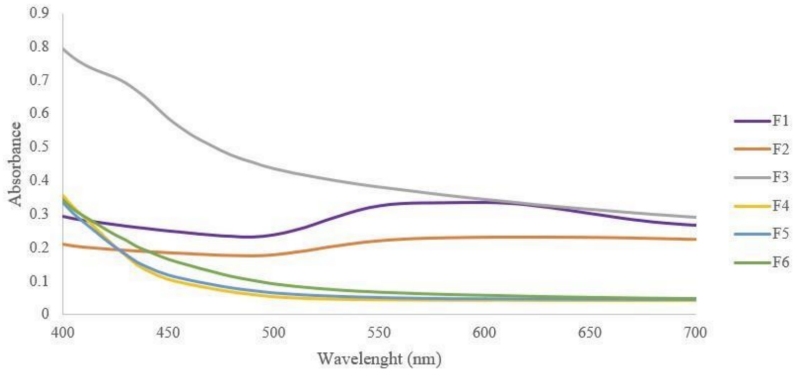


Figure 6. UV–Visible Spectra of Bio-Synthesized AuNPs (F1-F6)

The six gold nanoparticle synthesis formulas were analyzed for their maximum wavelength (λ_{max}), which varied across the formulations (Figure 6). The maximum wavelength of the $HAuCl_4$ solution and F1 were 310 nm and 500-600 nm, respectively (Figure 7).

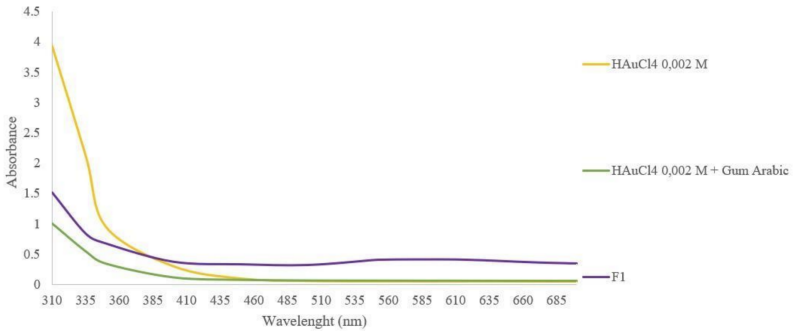


Figure 7. Comparison of the $HAuCl_4$ and F1 Wavelengths Curve

The colour of the solution changed from a slightly cloudy yellow to a clear white after adding 2 mM quercetin for 40 minutes. At 62 minutes, the colour shifted to purple streaks, which became thicker until the 90th minute (Figure 8).

Figure 8. The Colour Change During the Synthesis Process of F1

The combination of the $HAuCl_4$ solution with gum Arabic, a natural stabilizer. The gum Arabic solution helps stabilize the gold chloride solution, preventing aggregation and promoting the effective dispersion of gold ions. This stabilization is essential for the successful formation of gold nanoparticles. The results of this mixture were analyzed using UV-Vis spectrophotometry, confirming that the highest absorbance peak occurred at 310 nm, which indicates the stability and uniformity of the solution. This combination is critical for ensuring that the nanoparticle synthesis process proceeds smoothly, ensuring that the gold ions are ready for reduction in the following steps.

3.4. Characterization of Gold Nanoparticles

The stability of the gold nanoparticles was assessed over two months by monitoring their maximum wavelength using a UV-Vis spectrophotometer weekly. This was to ensure that the gold nanoparticles did not revert to the $HAuCl_4$ solution during storage. The maximum wavelength shift of the gold nanoparticles was observed to remain within the 500-600 nm range (Figure 9). The organoleptic stability of the gold nanoparticles was monitored for two months, at months 0, 1, and 2. Sensory observations revealed a fading purple colour (Figure 10). The storage conditions, duration, and exposure to light can influence nanoparticle size due to aggregation. Aggregation can occur due to storage factors and zeta potential values outside the acceptable range of -30 mV to +30 mV. The zeta potential value of the gold nanoparticles was -12.2 mV. Particles with zeta potentials between -10 mV and +10 mV are considered neutral and prone to aggregation [29].

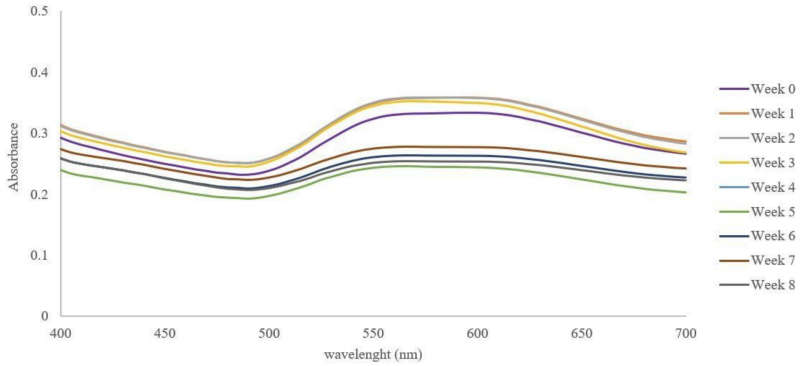


Figure 9. Stability Analysis of Gold Nanoparticles

Figure 9 presents the stability analysis of the gold nanoparticles over an 8-week period. The stability was monitored by tracking the maximum wavelength using a UV-Vis spectrophotometer, confirming that the gold nanoparticles remained stable within the 500-600 nm range. This observation ensures that the gold nanoparticles did not revert to the $HAuCl_4$ solution during storage. The consistency in the absorption spectrum across the weeks suggests that the nanoparticles maintained their stability, with no significant aggregation occurring over the duration of the study. This stability is critical for ensuring the reliability of the gold nanoparticles in future applications, particularly in drug delivery systems.

Figure 10. Colour Change Analysis of Gold Nanoparticles

Figure 10 show the color change of the gold nanoparticles over a two-month period, showing the visual changes at 0, 1, and 2 months. At month 0, the solution appears dark purple, and by month 1, it shows a noticeable fading of the color. By the second month, the color has lightened further, suggesting some degree of nanoparticle aggregation. This observation correlates with the stability analysis in Figure 9, indicating that while the gold nanoparticles remained stable in terms of their absorption characteristics, their visual color change may be attributed to storage factors and slight aggregation, which could affect their long-term usability in applications such as drug delivery.

3.5. Characterization of Gold Nanoparticles

The gold nanoparticles were characterized using a particle size analyzer. The particle sizes ranged from 35.03 to 580.41 nm, with an average particle size of 116.7 nm (Figure 11). The polydispersity index was 0.293, indicating a relatively low degree of particle size variation, as it was below 0.4 [30]. This suggests that the nanoparticles have the potential for use in nanomedicine, which often requires particles smaller than 200 nm [31, 32]. However, the zeta potential produced was not optimal for gold nanoparticles (Table 2). The ideal zeta potential range for gold nanoparticles is below -30 mV or above +30 mV [33]. A zeta potential between -10 mV and +10 mV indicates aggregation. If the zeta potential falls within this range, nanoparticles can aggregate to form larger microparticles. The poor zeta potential may have contributed to the observed colour change from dark purple to light purple.

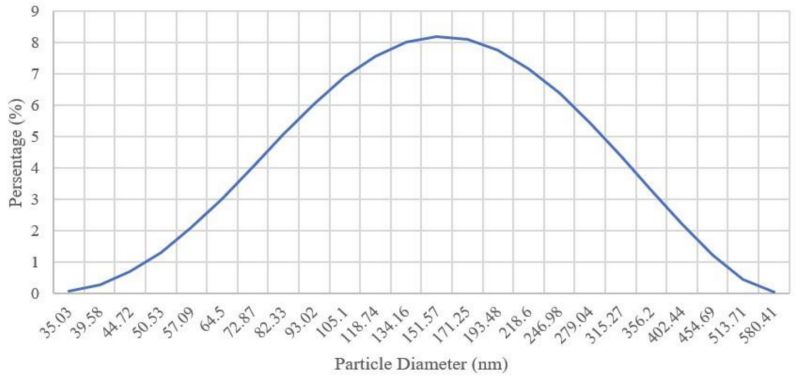


Figure 11. Colour Change Analysis of Gold Nanoparticles

Figure 11 shows the particle size distribution of the gold nanoparticles, obtained through the particle size analyzer. The particle diameters range from 35.03 nm to 580.41 nm, with an average size of 116.7 nm. The graph illustrates the typical distribution curve for nanoparticles, where the majority of particles fall within a certain size range. The polydispersity index of 0.293 indicates a relatively low degree of size variation, suggesting that the nanoparticles are fairly uniform in size, which is ideal for applications in nanomedicine. However, the broad distribution of particle sizes also points to the need for optimization to achieve a more

consistent size for specific applications. The observed color change from dark purple to light purple in the nanoparticles may be associated with variations in particle size and the zeta potential, as explained in the text.

Table 2. Characterization of F1 Gold Nanoparticles

Parameter	Unit	Result
Particle Size	nm	116.7
Zeta Potential	mV	-12.2
Polydispersity Index	-	0.293

Table 2 shows the characterization results of F1 gold nanoparticles. The particle size was reported to be 116.7 nm, which is within the ideal size range for nanomedicine applications, where particles smaller than 200 nm are usually preferred. The zeta potential was measured at -12.2 mV, indicating a slightly negative surface charge. Although this value is not optimal for gold nanoparticles, it does indicate stability; however, nanoparticles with a zeta potential between -30 mV and +30 mV are ideal to avoid aggregation. The polydispersity index of 0.293 indicates that the gold nanoparticles have a relatively low degree of size variation, which is beneficial for ensuring consistency and stability in nanoparticle formulations.

3.6. Tyrosinase Assay on Gold Nanoparticles

The optimal gold nanoparticle formulation (F1) was evaluated for its tyrosinase inhibitory activity using a tyrosinase enzyme. The study compared the IC_{50} values of the standard solution (kojic acid) and the F1 gold nanoparticle solution. The IC_{50} value represents the concentration of a compound required to inhibit a biological or biochemical function by 50% [34]. The tyrosinase inhibitory activity of gold nanoparticle samples of Quercetin (F1) at various concentrations (9457, 4728.5, 295.53, 147.76, and 73.88 µg/mL) exhibited inhibition rates of 92.2%, 92.2%, 16.3%, 8.83%, and 3.4%, respectively. As shown in Table 3, the resulting R2 value is 0.9702, and the IC_{50} value is 970 µg/mL. The standard tyrosinase (kojic acid) enzyme inhibitory activity test results for various concentrations (125; 62.5; 31.25; 15.625; and 7.8125 µg/mL) were 89.95%, 69.26%, 38.04%, 21.91%, and 5.52%, respectively. The R2 value for the standard tyrosinase was 0.9843, and the IC_{50} value was 36.7537 µg/mL [35].

Table 3. The IC_{50} of Tyrosinase Assay

Data	a	b	R^2	IC_{50} (µg/mL)
Kojic acid	-62.427	31.193	0.9843	36.7537
Gold nanoparticles	-92.869	20.774	0.9702	970

The IC_{50} value of gold bio-nanoparticles (F1) was 970 µg/mL, indicating weak tyrosinase inhibitory activity. The high IC_{50} value may be attributed to temperature variations during the tyrosinase assay. Temperature is a crucial factor in enzyme-catalyzed reactions, and improper temperature control can lead to enzyme denaturation. In addition to temperature, the prolonged testing time of four weeks may have contributed to the reduced tyrosinase inhibitory activity of the gold nanoparticles due to aggregation. Previous studies have reported lower IC_{50} values for gold nanoparticles synthesized using Panax ginseng leaf extract (16.06 µg/mL) and ginseng berry extract (6.6 µg/mL) as reducing agents. The lower IC_{50} values in these studies were likely due to the purification of nanoparticles using sterile distilled water and centrifugation, which was not performed in this study. While the F1 sample demonstrated weak tyrosinase inhibitory activity compared to the literature, it is possible that these gold bio-nanoparticles still retain some inhibitory activity.

4. MANAGERIAL IMPLICATION

The green synthesis of gold nanoparticles using quercetin as a reducing agent presents significant opportunities for biotechnological innovations. This environmentally friendly approach, which reduces reliance on toxic chemicals and high-energy processes, offers a sustainable alternative for nanoparticle production. For businesses involved in nanomedicine or drug delivery systems, this method can reduce operational costs and increase production scalability. Companies should consider adopting this green synthesis strategy to meet the growing demand for sustainable practices in manufacturing. Additionally, the stability and unique properties of the synthesized gold nanoparticles suggest their potential use in therapeutic applications, such as targeted

drug delivery. Managers in the pharmaceutical sector should explore collaborations with research institutions to leverage this technology and develop innovative drug delivery systems.

Furthermore, the development of gold nanoparticles using quercetin presents a promising opportunity for biopreneurs to capitalize on the growing interest in nanotechnology. Given the relatively low cost and eco-friendly nature of the synthesis process, biopreneurs can create cost-effective, high-quality gold nanoparticle products for a variety of applications, including medical, cosmetic, and agricultural industries. By focusing on the commercialization of these nanoparticles, businesses can provide novel solutions in drug delivery, cancer treatment, and other biomedical fields. Moreover, this method aligns with the global shift towards sustainability, making it an attractive business model for those looking to invest in future-oriented, environmentally-conscious products.

5. CONCLUSION

Quercetin has proven to be an effective reducing agent in the synthesis of gold nanoparticles, demonstrating its potential for use in various biomedical and industrial applications. The gold nanoparticles produced using quercetin have an average particle size (Z-average) of 116.7 nm, which is ideal for nanomedicine and drug delivery applications. With a polydispersity index of 0.293, these nanoparticles show a relatively low degree of size variation, suggesting uniformity in particle size. This consistency is crucial for ensuring the stability and efficacy of nanoparticle-based systems, particularly in controlled drug release and targeting.

The synthesized gold nanoparticles also exhibit a zeta potential of -12.2 mV, which indicates a slightly negative surface charge, providing some stability against aggregation. While the zeta potential value is not optimal for long-term stability, it is still within a range that can prevent significant aggregation over short periods, as demonstrated by their stability for up to eight weeks. The stability of these nanoparticles is an essential factor for their use in drug delivery systems, where prolonged shelf-life and consistent performance are crucial for medical applications.

Furthermore, the gold nanoparticles have demonstrated inhibitory activity against the tyrosinase enzyme, with an IC_{50} value of 970 µg/mL, making them promising candidates for cosmetic and therapeutic applications. This characteristic suggests their potential in treating hyperpigmentation and other skin-related conditions. The ability of quercetin-based gold nanoparticles to exhibit such biological activity adds an innovative edge to the biopreneurship space. As a sustainable and cost-effective method, this synthesis approach offers new possibilities for the development of nanoparticles for drug delivery, therapeutics, and other biotechnological innovations.

6. DECLARATIONS

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6.2. Author Contributions

Conceptualization: RD and PA; Methodology, Software, Validation: TP and RA; Formal Analysis: RP; Investigation: KC; Resources: RD and TP; Data Curation: PA and RA; Writing Original Draft Preparation: KC, RD, and PA; Writing Review and Editing: RA and RP; Visualization: TP; All authors, RD, PA, TP, RA, RP and KC, have read and agreed to the published version of the manuscript.

6.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.4. Funding

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6.5. Declaration of Conflicting Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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