



Bio-derived gold nanoparticles from rowan berries: toward eco-friendly nanotechnology

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Received: 22 October 2025 / Accepted: 13 January 2026

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Abstract This study presents the green synthesis and comprehensive characterization of gold nanoparticles (AuNPs) using aqueous extracts derived from *Sorbus aucuparia* L. (Rowan berries) harvested in Trabzon province, Türkiye. Initially, 100 g of the dried fruit material were thoroughly washed with deionized water to eliminate dust and surface contaminants and subsequently dried under appropriate conditions. The dried fruits were boiled in 500 mL of deionized water for 60 min to obtain the bioactive extract, which was then filtered using Whatman filter paper. Chloroauric acid trihydrate ($\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$, 99.9%) was used as the gold precursor at three different concentrations: 0.1 mM, 0.2 mM, and 0.3 mM. To each concentration, 0.3 mL or 0.5 mL of the fruit extract was added. The reaction mixtures were prepared by combining the extract and 70 mL of the HAuCl_4 solution and stirred gently to ensure uniform dispersion. Microwave-assisted synthesis was employed using a standard household microwave oven at power levels of 180 W, 360 W, and 600 W, for durations varying between 1 and 15 min. Each experimental condition was repeated in triplicate to ensure reproducibility and statistical reliability. Characterization of the resulting AuNPs was performed using UV–Vis spectroscopy, TEM, FTIR, XRD, and Zetasizer analysis. The optimal synthesis conditions were identified as 0.1 mM HAuCl_4 concentration with 0.3 mL of *Sorbus aucuparia* L. extract under 360 W microwave irradiation. UV–Vis analysis revealed a distinct surface plasmon resonance (SPR) peak, confirming the successful formation of gold nanoparticles. TEM images showed that the AuNPs were predominantly spherical with a mean particle size of 17.750 ± 3.606 nm, ranging from 10.230 to 28.687 nm. The crystallite size calculated from XRD was approximately 12.38 nm. Dynamic Light Scattering (DLS) analysis demonstrated an average hydrodynamic diameter of 45.25 ± 7.9 nm in aqueous suspension. The zeta potential was measured at -15.2 ± 7.49 mV, indicating moderate colloidal stability. The polydispersity index (PDI) was found to be 0.581, suggesting a moderately polydisperse system. The produced AuNPs remained stable without significant aggregation or precipitation for a period of 2–3 months when stored under ambient conditions.

Abbreviations

RB	Rowan berries
AuNPs	Gold nanoparticles
$\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$	Chloroauric acid trihydrate
SPR	Surface plasmon resonance
XRD	X-ray diffraction
FTIR	Fourier-transform infrared spectroscopy
TEM	Transmission electron microscopy
DLS	Dynamic Light Scattering
PDI	Polydispersity index
ZP	Zeta potential

1 Introduction

In recent years, there has been a growing interest in the utilization of natural raw materials, particularly those with potent antioxidant properties, owing to their numerous health benefits [1]. Among these, plants traditionally used in folk medicine are regaining

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scientific attention, with species from the *Sorbus* genus, commonly known as rowan, emerging as noteworthy candidates [1]. *Sorbus aucuparia* L., also referred to as mountain ash or rowanberry, is a slender deciduous tree from the Rosaceae family that can reach heights of up to 15–20 m and grows extensively across the Northern Hemisphere, from the European Atlantic to the Kamchatka Peninsula and eastern China [2–5]. Eighteen *Sorbus* taxa are naturally distributed [6–8], with the Eastern Anatolia region showing the highest diversity of species within the Türkiye [9]. *S. aucuparia* and *S. torminalis* species have been found in many areas at an altitude of 1000 m. The regions with the least species diversity are the Mediterranean and Southeastern Anatolia regions. In this regard, it has been determined that the northern regions of the country have both greater diversification and a higher number of individuals [9]. The fruits of *Sorbus* species are a rich source of bioactive compounds such as sugars, organic acids, phenolic acids, flavonoids, anthocyanins, tannins, cyanogenic glycosides, vitamins, and essential minerals [1, 10–12]. Owing to this complex phytochemical profile, various parts of the plant exhibit a wide range of pharmacological properties, including antioxidant, antidiabetic, anti-inflammatory, antihyperlipidemic, antibacterial, antiviral, antifungal, anticancer, vasoprotective, hepatoprotective, cardioprotective, and neuroprotective activities [13–16]. In traditional and alternative medicine, rowan fruits have been employed in the management of several health disorders, such as diabetes, metabolic syndrome, arthritis, rheumatism, gastrointestinal conditions (e.g., gastritis, irritable bowel syndrome), as well as hepatic and gallbladder diseases [1, 17, 18]. Although its berries, characterized by their small, red–orange appearance, and bitter taste, are not widely consumed as food, they have long been integrated into medicinal practices for their diuretic, antidiabetic, anti-inflammatory, and antimicrobial properties [19–22]. Parallel to the rediscovery of medicinal plants, the field of nanotechnology has witnessed a paradigm shift toward environmentally sustainable synthesis methods. Green synthesis of nanoparticles, which leverages biological resources such as bacteria, fungi, yeast, and plant extracts, has emerged as a promising alternative to conventional physicochemical techniques [22]. These biogenic approaches utilize natural biomolecules—metabolites, proteins, polysaccharides, and amino acids—not only to reduce metal ions but also to stabilize the resulting nanoparticles [23, 24]. Compared to traditional methods that often require harsh chemicals and generate hazardous byproducts, green synthesis offers advantages such as low toxicity, environmental friendliness, and cost-effectiveness, making it particularly attractive for biomedical applications [22, 25]. Moreover, the use of medicinal plants in nanoparticle synthesis introduces an added layer of functionality. The bioactive compounds present in these plants become embedded in the biological corona surrounding the nanoparticles, thereby enhancing their biocompatibility, therapeutic efficacy, and long-term stability [22, 23]. In recent years, nanomaterials have garnered considerable attention due to their remarkable characteristics, including large surface area, enhanced reactivity, and distinctive optical and electronic behaviors [26]. These nanoscale-specific attributes contribute to superior catalytic performance, tunable photoactivity, and improved mechanical strength, thereby broadening their utility across various domains [26].

In response to the growing challenges posed by industrialization and urbanization, nanotechnology has emerged as a leading innovation in scientific research, offering promising solutions for the remediation of environmental contaminants [26]. Green synthesis of nanoparticles (NPs) is an eco-friendly approach that enables the production of metallic NPs without causing environmental harm [26]. It is considered cost-effective, sustainable, and straightforward to implement [26]. Unlike conventional synthesis methods, which often involve hazardous chemicals, high energy consumption, and generate toxic waste, green synthesis is increasingly preferred due to its numerous environmental and economic benefits [26]. The rise of green nanotechnology has become increasingly significant for phytotherapy, offering improvements in drug delivery, enhanced bioavailability, and minimized off-target effects [27]. Nanotechnology focuses on the design and utilization of materials ranging in size from 1 to 100 nm [27–30]. Green synthesis methods employ natural substances as reducing, capping, and stabilizing agents in a simple one-step process. Among these, plant-mediated synthesis has been shown to be more cost-effective compared to microbial approaches [27, 31, 32]. The vast diversity of plant species represents a rich source of phytochemicals, which can be harnessed for the eco-friendly synthesis of metallic nanoparticles with superior biological functionalities [27, 33–35]. Microwave-assisted extraction (MAE) is an efficient and adaptable technique characterized by reduced extraction time and lower energy requirements. The application of microwave energy generates localized high-temperature zones, which facilitate the breakdown of cell walls—particularly in plant-based materials. This enhanced cellular disruption accelerates the release of bioactive compounds, allowing for their rapid and effective transfer into the solvent [36]. Gold has long been recognized in traditional medicine, particularly in the *Donguibogam*, for its calming, nourishing, and detoxifying properties [37]. In recent years, research conducted in Europe and the USA has highlighted gold's diverse benefits, including skin revitalization, improved blood circulation, relief of arthritis pain, immune system support, and enhancement of brain function [37]. Additionally, gold nanoparticles have demonstrated strong antioxidant capabilities by inhibiting the production of reactive oxygen species (ROS) and effectively scavenging free radicals [37, 38]. Gold nanoparticles (AuNPs) have emerged as promising agents in cancer therapy and diagnostics, attracting significant research interest due to their unique physicochemical properties, including excellent stability, biocompatibility, high thermal conductivity, distinctive optical and electrical characteristics, large surface area-to-volume ratio, tunable surface chemistry, and potential for multifunctionalization [39].

To date, there has been no study in the scientific literature reporting the synthesis of gold nanoparticles using the microwave-assisted method from *Sorbus aucuparia* L. fruit extract obtained via MAE, a process that aligns with the principles of green chemistry. In this context, the present study aimed to establish an environmentally friendly synthesis route for gold nanoparticles, utilizing microwave-assisted green synthesis with fruit extracts of *S. aucuparia* L. collected from the Trabzon province of Türkiye. The extract was obtained for the first time using the MAE technique. The resulting gold nanoparticles were synthesized in accordance with green chemistry principles and subsequently characterized using ultraviolet–visible spectroscopy (UV–Vis), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and Zetasizer analysis.

Fig. 1 RB-AuNPs are green-synthesized by reducing gold ions using *Sorbus aucuparia* L. fruit extract



2 Materials and methods

2.1 Extraction of *Sorbus aucuparia* L. fruit extract

Sorbus aucuparia L. fruits were collected from the Düzköy district of Trabzon, located in the Eastern Black Sea Region of Türkiye. After its taxonomic identification was verified by Prof. Dr. Bedri SERDAR, the plant sample was archived under the code KATO:20,782 in the Herbarium of the Department of Forest Engineering, Karadeniz Technical University, Trabzon, Türkiye. The fruits were thoroughly cleaned by repeated washing with deionized water to remove dust and other contaminants, and subsequently dried under appropriate conditions. Hundred gram of dried fruits of *Sorbus aucuparia* L. were boiling for 60 min in 500 mL of deionized water and filtered with Whatman filter paper.

2.2 Production of AuNPs

Aqueous solutions of chloroauric acid trihydrate ($\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$, 99.9%, Sigma-Aldrich) were prepared at four different concentrations: 0.1 mM, 0.2 mM, and 0.3 mM. To each solution, varying volumes of *Sorbus aucuparia* L. fruit extract (0.3 mL and 0.5 mL) were added. In a typical synthesis, approximately 0.3–0.5 mL of the fruit extract was mixed with 70 mL of the HAuCl_4 solution and gently stirred to ensure homogeneous mixing. The reaction mixtures were then subjected to microwave-assisted synthesis using a conventional household microwave oven. Irradiation was performed at different power levels (180 W, 360 W, and 600 W) for durations ranging from 1 to 15 min, depending on the experimental design. Each experimental condition was carried out in triplicate to ensure reproducibility. The formation of gold nanoparticles (AuNPs) was monitored visually through a gradual color change in the reaction solution, a well-known indicator of colloidal gold formation. Samples were collected at different time intervals based on the intensity and progression of this color shift. The presence of AuNPs was further confirmed by the detection of characteristic surface plasmon resonance (SPR) bands using UV–visible spectroscopy. To optimize the nanoparticle synthesis, key parameters such as HAuCl_4 concentration, extract volume, reaction time, and microwave power were systematically varied. Following synthesis, the AuNPs were purified through triple centrifugation at 10,000 rpm for 15 min. The resulting nanoparticle pellets were re-dispersed in deionized water and stored at 4 °C for further characterization and application studies.

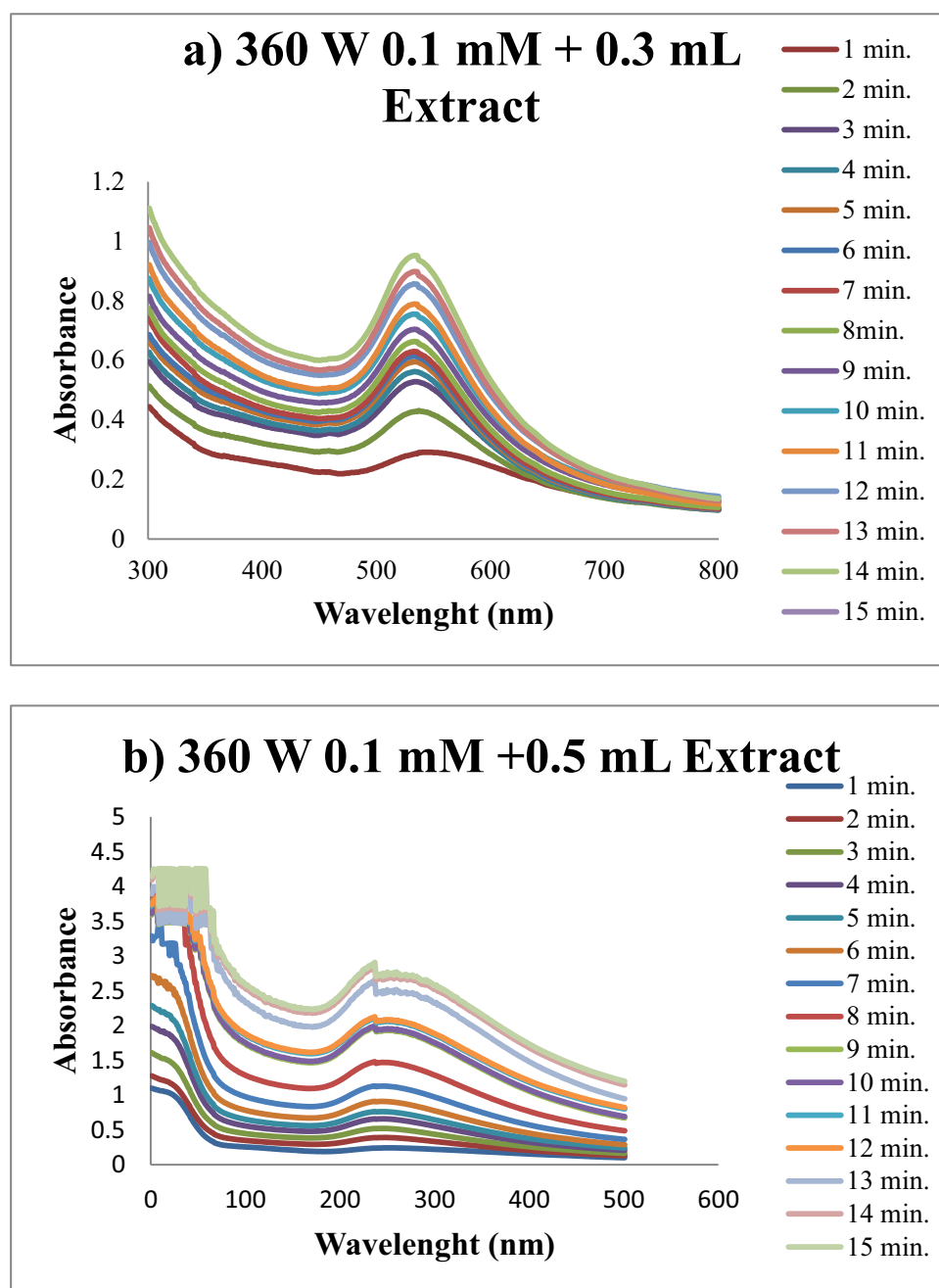
3 Results and discussion

3.1 Green synthesis of rowanberries-gold nanoparticles (RB-AuNPs)

The green synthesis of RB-AuNPs was monitored both visually and by UV–Vis spectroscopy. Rowanberry extract effectively reduced the gold salt, resulting in the formation of RB-AuNPs (Fig. 1). Figure 1 presents a schematic overview of the synthesis pathway for PGL-AuNPs. Figure 1 clearly demonstrates a gradual color transition from light yellow to purple, providing a strong visual indication of nanoparticle formation, corresponding to the surface plasmon resonance (SPR) characteristic of the nanoparticles. This color change was observed during the reaction with varying concentrations of *Sorbus aucuparia* L. fruit extract and is characteristic of the surface plasmon resonance (SPR) associated with gold nanoparticles (AuNPs) of different sizes in solution. UV–Vis spectroscopy was performed in the range of 300–800 nm (Shimadzu UVP-1240 spectrophotometer) to further confirm the synthesis.

In Fig. 2, at a power of 360 W and a concentration of 0.1 mM, sharper and higher peaks were obtained with 0.3 mL and 0.5 mL *Sorbus aucuparia* L. fruit extracts, with the 0.3 mL volume showing a more pronounced and narrow peak. In Fig. 3, measurements were conducted at different concentrations (0.2 mM and 0.3 mM) using 0.3 mL of *Sorbus aucuparia* L. fruit extract at the same power of 360 W. Based on the data obtained from Figs. 1 and 2, the best result was achieved using 0.3 mL of fruit extract at 0.1 mM concentration under 360 W power. According to these results, in Fig. 4, after 8 min of irradiation at power levels of 180, 360, and 600 W, the maximum absorption peak of AuNPs was observed at 533 nm, with corresponding absorbance values of 0.34, 0.63, and 0.98, respectively. For RB-AuNPs, a distinct absorption peak was observed at 533 nm, confirming the formation of nanoparticles in the solution. Although the absorbance was highest at 600 W, the broader bandwidth observed at this power level indicates less homogeneous nanoparticle formation. Therefore, 360 W, where a sharper and more distinct peak was observed, was

Fig. 2 Surface plasmon resonance (SPR) absorption spectra of gold nanoparticles synthesized at 360 W using 0.1 mM $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ concentration, **a** 0.3 mL and **b** 0.5 mL fruit extract



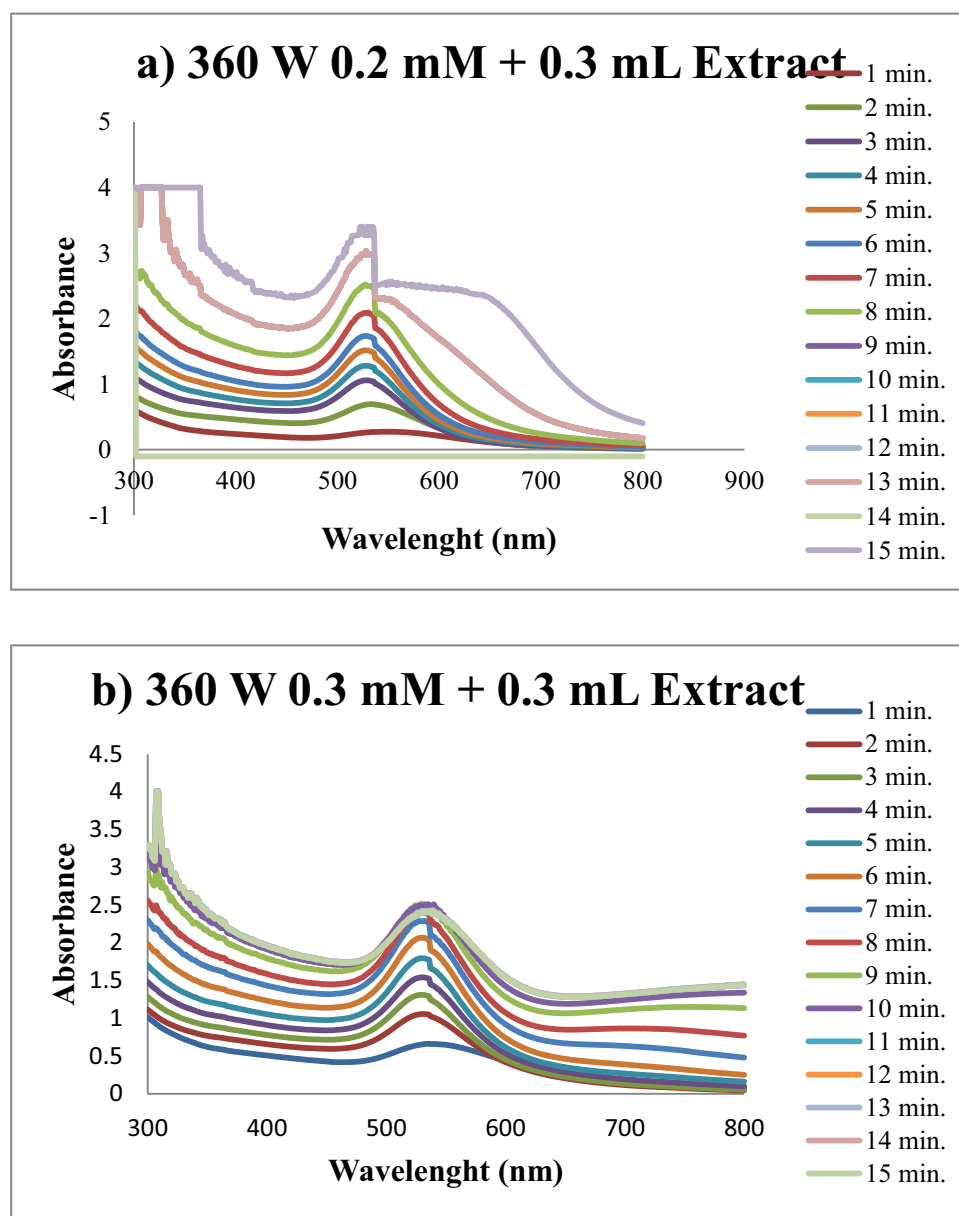
considered the most suitable condition. RB-AuNPs were successfully synthesized using 0.3 mL of *Sorbus aucuparia* L. fruit extract at a concentration of 0.1 mM and under 360 W power using the microwave-assisted extraction method. The clear appearance of SPR band confirmed the successful formation of the nanoparticles.

The fact that the UV–Vis spectra of RB-AuNPs did not show any significant changes after 2 months, as shown in Fig. 5, indicates that these nanoparticles are stable. However, a spectral decrease was observed after 3 months, and the RB-AuNPs maintained their stability for up to 3 months at most (Fig. 5).

3.2 Characterization of *Sorbus aucuparia* L. fruit extract

Gold nanoparticles (AuNPs) were comprehensively characterized using various analytical techniques, including UV–Visible spectroscopy, TEM, XRD, FT-IR, and DLS via Zeta-sizer. The morphology and particle shape of the synthesized AuNPs were examined using TEM (Hitachi HT-7700), which provided high-resolution images of the crystalline structures. The TEM images presented in Fig. 6 confirm the successful synthesis of gold nanoparticles (AuNPs) under the conditions of 0.1 mM $\text{HAuCl}_4 \cdot 4\text{H}_2\text{O}$, 0.3 mL

Fig. 3 Surface plasmon resonance (SPR) absorption spectra of gold nanoparticles synthesized 360 W, using **a** 0.2 mM and **b** 0.3 mM $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ concentration, 0.3 mL fruit extract

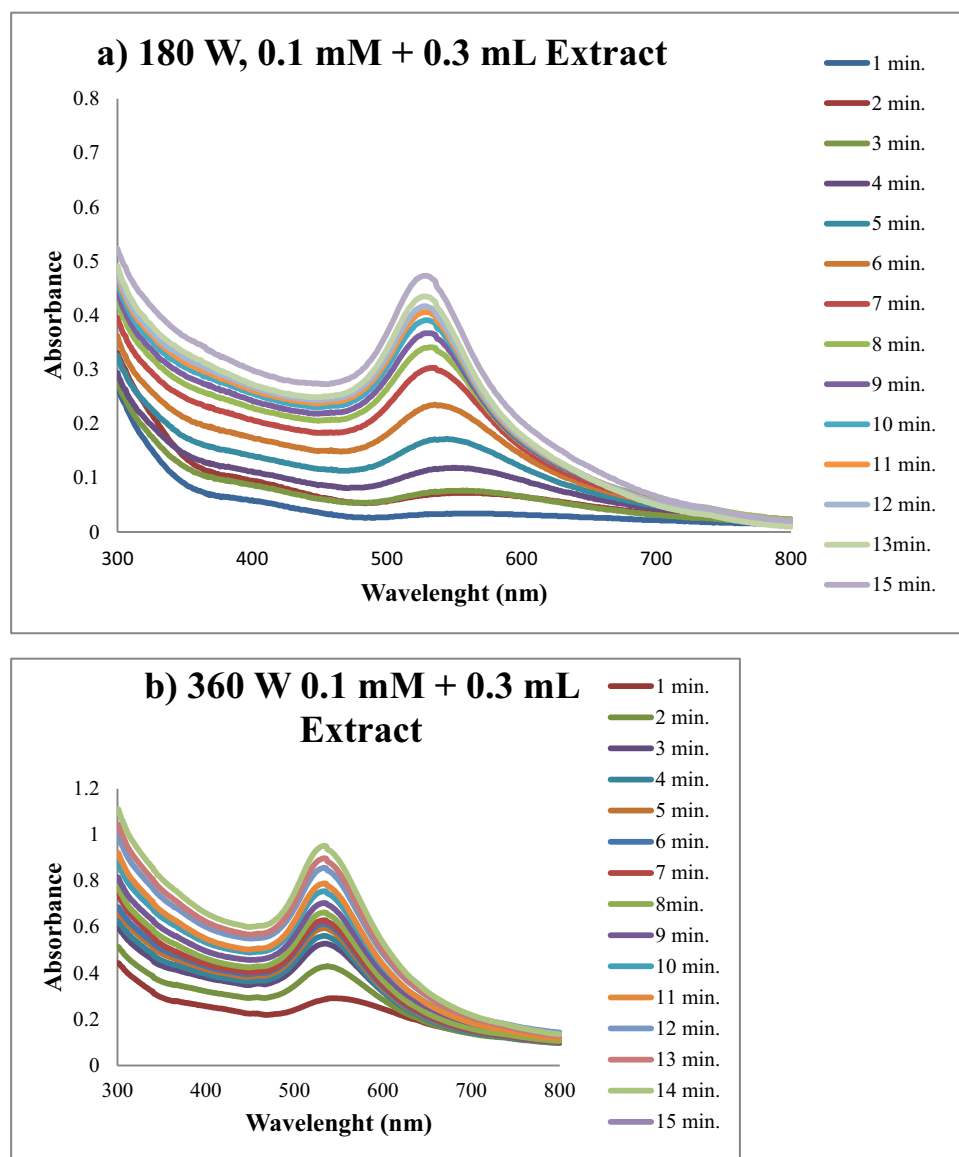


Sorbus aucuparia L. fruit extract at 360 W microwave-assisted extraction. The spherical morphology of the AuNPs observed in the micrographs aligns well with the shape of the surface plasmon resonance band observed in the corresponding UV–Vis spectrum, supporting their characteristic optical properties. From the analysis of Fig. 6a, the size of DKL-AuNPs was found to range between 10.230 and 28.687 nm, with a mean diameter of 17.750 ± 3.606 nm (Fig. 6b). These findings are consistent with the TEM-based results reported by [22], who observed the core particles range found was 90–100 nm, with uniformity in shape and size distribution, measured at a different scale. RB-AuNPs and Rowanberries-mediated gold nanoparticles (RB-AuNPs) formed within 5 s at room temperature. (Gold salt concentration was 4 mM.)

The crystalline nature and phase identification of the nanoparticles were further investigated by X-ray diffraction (XRD) using a Panalytical X'Pert³ Powder diffractometer. The crystallite size (D_c) was calculated using the Scherrer equation based on the full width at half maximum (FWHM) of the characteristic diffraction peaks. According to Fig. 7, which presents the XRD pattern of gold nanoparticles (AuNPs) synthesized using aqueous rowan berries fruits extract, the gold nanoparticles exhibit a completely crystalline nature. Distinct Bragg reflection peaks are observed at 2θ values of 38.26° , 44.45° , 64.64° , and 77.63° , corresponding to the lattice planes (111), (200), (220), and (311), respectively.

These reflections closely match the characteristic peaks of metallic gold with a cubic structure, as documented in JCPDS card no. 04–0784 [40–42], confirming the phase purity and crystallinity of the synthesized AuNPs. The Scherrer equation was applied to the

Fig. 4 Surface plasmon resonance (SPR) absorption spectra of gold nanoparticles synthesized at different microwave powers **a** 180 W, **b** 360 and **c** 600 W using 0.1 mM HAuCl₄·3H₂O concentration and 0.3 mL fruit extract



(111) diffraction peak to estimate the average crystallite size, which was found to be 12.38 nm. In the literature, the characterization of gold nanoparticles synthesized from rowan berries fruit extract using the XRD technique has not been reported.

The FT-IR spectra of the samples were evaluated using an open spectrum library for bioactive compounds and an FT-IR spectrum database to identify the chemical linkages. To identify the functional groups potentially involved in nanoparticle stabilization, FT-IR analysis was performed using a PerkinElmer Frontier spectrometer in the range of 4000–550 cm⁻¹. Different surface patterns were observed in the samples (Fig. 7). FTIR analysis provided further confirmation that functional groups present in the rowan berries extract were involved in the nanoparticle synthesis. The FTIR spectra of the biosynthesized AuNPs from rowan berries fruits extract showed no significant differences compared to the spectra of the pure extract, indicating that the same functional groups remained active on the surface of the synthesized AuNPs (Fig. 8).

The FT-IR analysis of the RB-AuNPs confirmed the presence of various functional groups. The RB-AuNPs sample shows medium or strong absorption bands about at 3266, 2931, 1714, 1404, 1260, 1023, and 887 cm⁻¹. FT-IR analysis clearly indicated that the synthesized nanoparticles were coated with various biological compounds, contributing to their stability [43, 44]. Moreover, the analysis revealed that hydroxyl (–OH) groups, particularly from flavonoid compounds, played a key role in the reduction process and acted as a stabilizing corona around the nanoparticles. These –OH groups interact with metal ions, facilitating the reduction of cationic gold ions (Au⁺) to elemental gold (Au⁰), resulting in the formation of AuNPs.

Finally, the hydrodynamic diameter and zeta potential of the AuNPs dispersed in aqueous solution were analyzed using a Zeta-sizer, providing insight into their colloidal stability and size distribution. Dynamic Light Scattering (DLS) analysis was performed to determine the hydrodynamic diameter and zeta potential of the synthesized nanoparticles. According to the results, RB-AuNPs

Fig. 4 continued

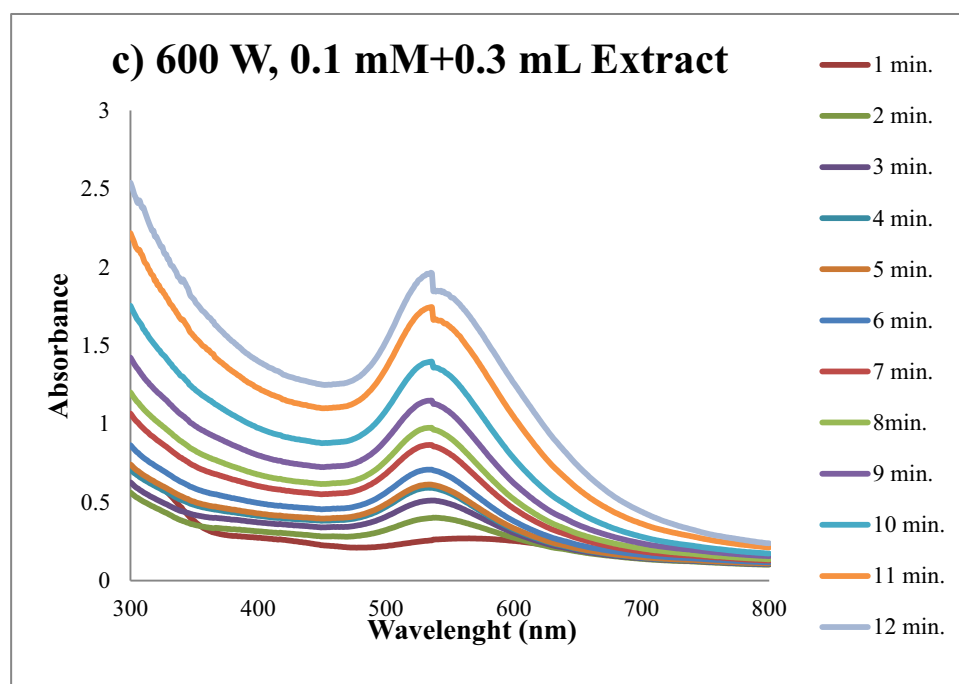
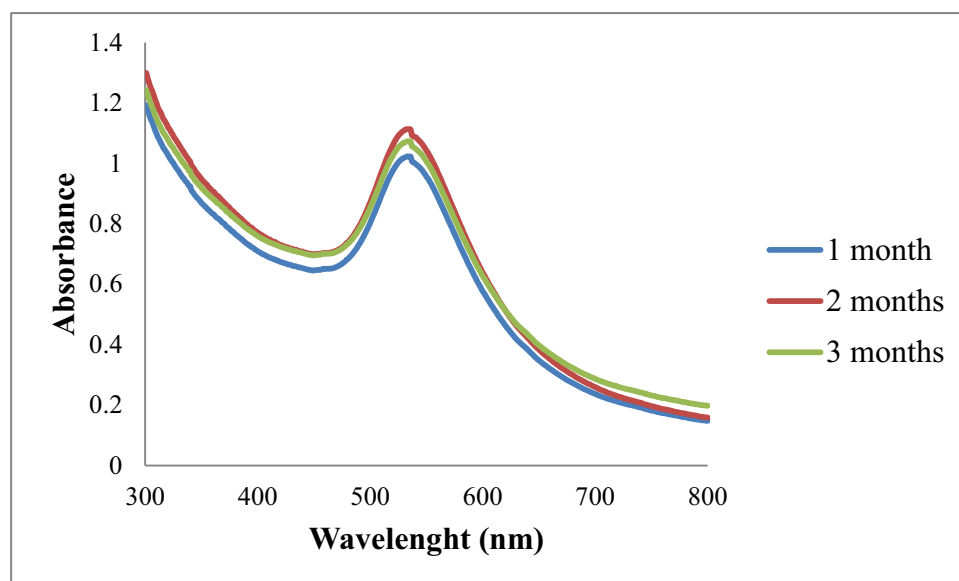


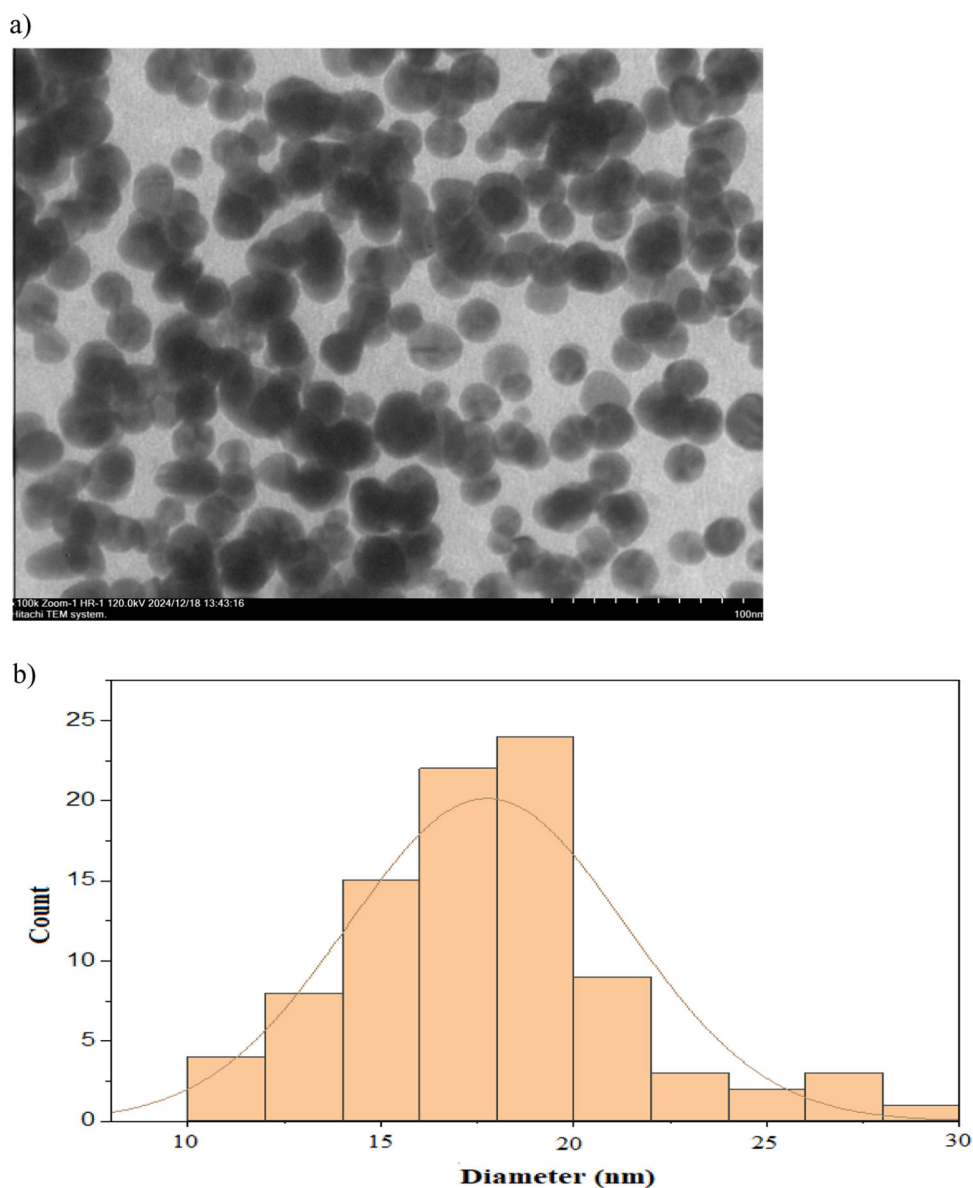
Fig. 5 UV-Vis spectra of RB-AuNPs recorded at different storage time intervals



exhibited a hydrodynamic size of 45.25 nm with a polydispersity index (PDI) of 0.581 (Fig. 9), Zeta potential measurements revealed that both nanoparticles carried a highly negative surface charge, with values of -15.2 mV for RB-AuNPs (Fig. 9b).

Singh and Mijakovic [22] reported the zeta potential value of rowan berries fruits extract *Sorbus aucuparia* (fruit) was -25.6 mV, RB-AuNPs had a size of 280.1 nm with a polydispersity index (PDI) 0.512. Nanoparticles exhibit increased stability as the magnitude of their zeta potential increases, particularly when the value becomes more negative [41, 42, 45]. In the case of DKL-AuNPs, their surfaces are coated with negatively charged phytoconstituents, which generate electrostatic repulsion between particles. This repulsive force prevents aggregation and contributes to the colloidal stability of the nanoparticles, as reflected in their negative zeta potential values. Furthermore, Dynamic Light Scattering (DLS) analysis reveals the distribution of particle sizes based on their hydrodynamic diameters. Since DLS measures particles in a solvated state, the observed sizes are typically larger than those determined by Transmission Electron Microscopy (TEM), which assesses particles in a dried state [46].

Fig. 6 TEM characterization of gold nanoparticles synthesized via the microwave-assisted method using 0.1 mM $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ and 0.3 mL *Sorbus aucuparia* L. fruit extract at 360 W, **a** TEM micrograph showing nanoparticle morphology (100 nm), **b** corresponding particle size distribution histogram



3.3 Statistical analysis

Each experiment was conducted in triplicate based on the specified analytical method. The results are reported as the mean $\pm$ standard deviation (SD), with a sample size of $n = 3$.

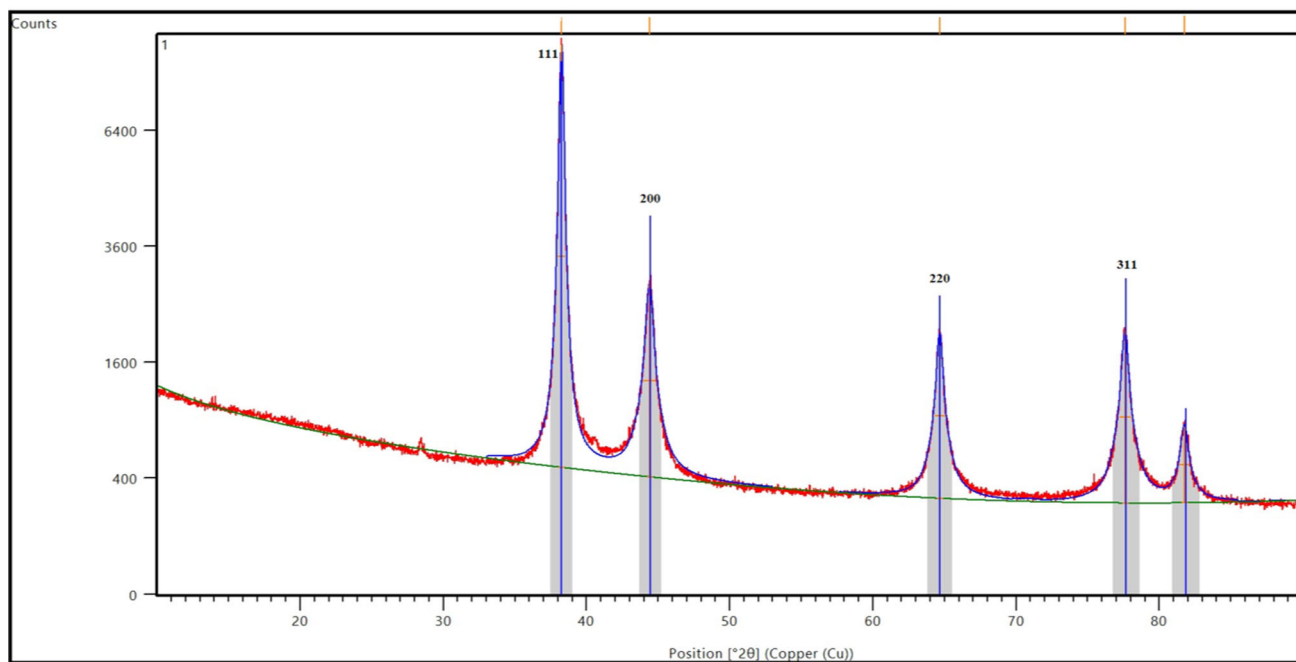


Fig. 7 XRD pattern of RB-AuNPs

Fig. 8 FTIR spectrum of RB-AuNPs

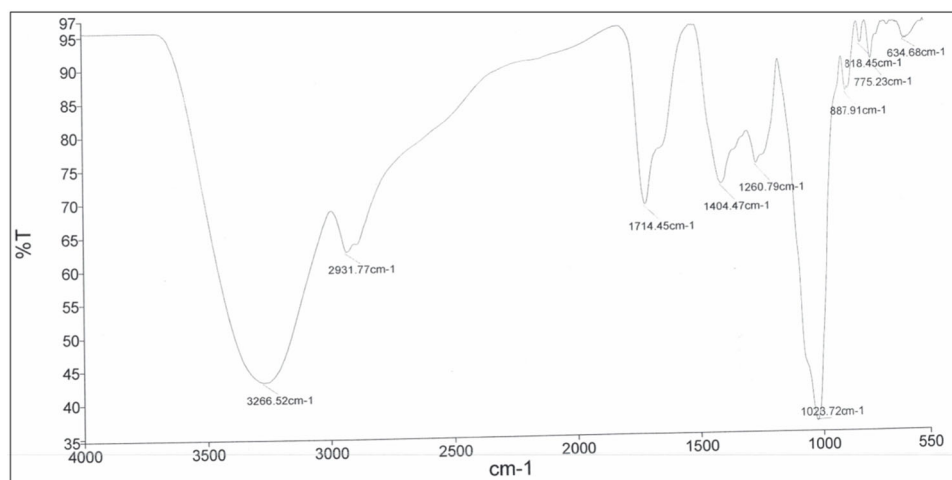
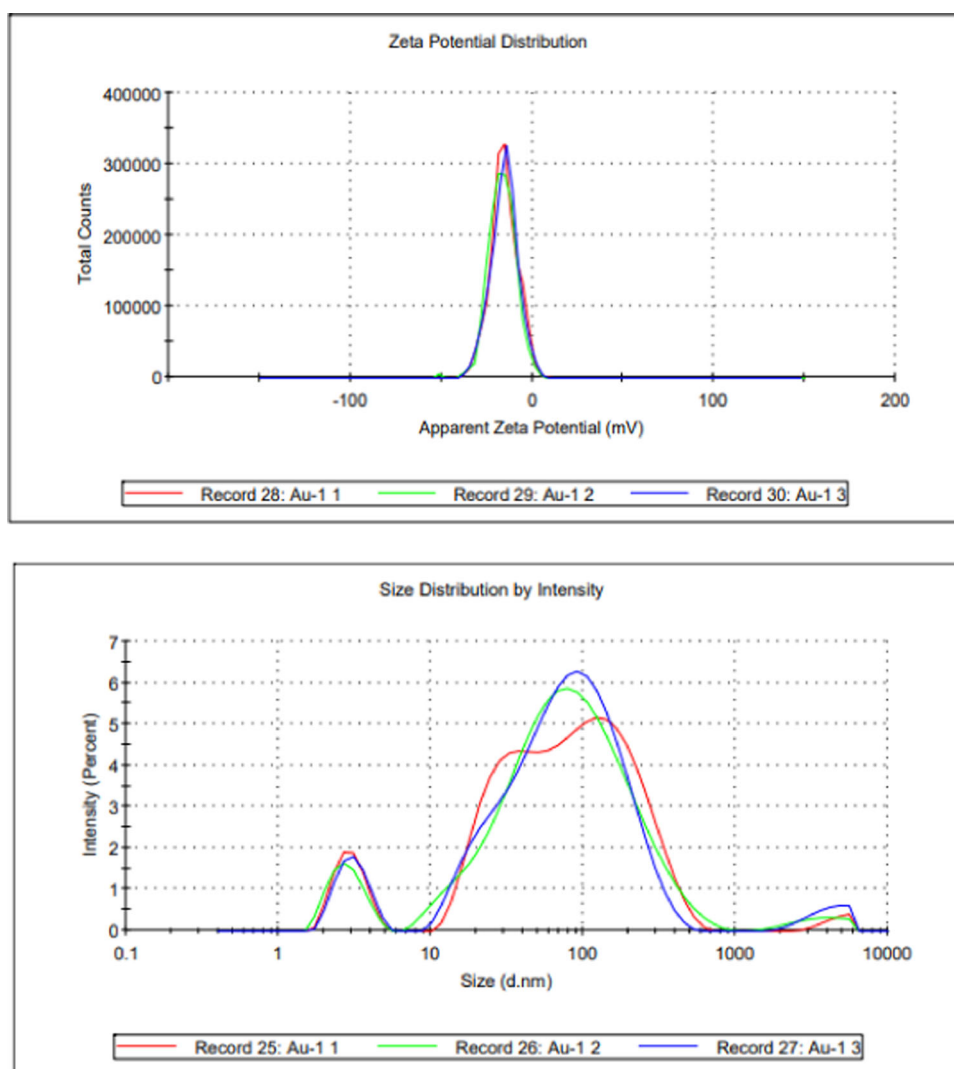


Fig. 9 Zeta potential distribution and size distribution by intensity of RB-AuNPs



4 Conclusion

According to the results, RB-AuNPs were successfully synthesized using a low-energy, environmentally friendly green synthesis method based on *Sorbus aucuparia* L. (Rowan Berries) fruit extracts. The aqueous extract derived from the fruits acted as both a reducing and stabilizing agent, indicating that the nanoparticle formation occurred through a biologically mediated process. This study is the first in the literature to report the rapid, cost-effective, and eco-friendly synthesis of gold nanoparticles using *Sorbus aucuparia* L. fruits collected from Trabzon, Türkiye. The phytochemical compounds present in the extracts played a crucial role in reducing and stabilizing gold ions, enabling a plant-based and sustainable transformation. The gold nanoparticles synthesized through this green approach possess significant potential for the development of innovative applications in medicine, pharmacology, the food industry, and materials science.

Acknowledgements The authors gratefully acknowledge the support of the Central Research Laboratories at Karadeniz Technical University and Atatürk University.

Author contributions Gönül Serdar contributed to the research, experimental studies, data visualization, formal analyses, and the writing of the manuscript. Memnune Kokoç was involved in the visualization of TEM data, statistical analyses, and manuscript preparation. Bedri Serdar contributed to plant identification, sample collection, and the writing of the manuscript.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This research was not funded.

Data availability The information presented in this manuscript is original and has not been published elsewhere. The manuscript includes several figures supporting the data.

Declarations

Conflict of interests The authors declare that there are no conflicts of interest related to this work.

Ethical Approval This research study has been conducted in accordance with established publication and research ethics standards.

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