RESEARCH PAPER

Biogenic Synthesis and Characterization of Gold Nanoparticles Using Aloe vera Gel Extract for Targeted Drug Delivery Applications

N. Ramakrishna[1], Ranadevan Rajakumaravelu[2], Ruchita Shrivastava[3], Dhiraj Vasant Bhavsar[4*]

[1]Assistant Professor, Department of Botany, Dr. B.R. Ambedkar Open University, Jubilee Hills, Hyderabad – 500033, Telangana, India

[2]Assistant Professor, Department of Biochemistry, Institute of Medical Sciences & SUM Hospital II, Siksha 'O' Anusandhan (Deemed to be University), Phulnakhara, Bhubaneswar, Odisha, India, Pin Code – 754001

[3]Senior Visiting Lecturer (JBS), Department of Botany, Govt. Homescience PG Lead College, Narmadapuram, MP, Pin Code – 461001

[4*]Assistant Professor, Department of Botany, Shri Anand College, Pathardi, Ahilynagar, Maharashtra | Email: bhavsardv@shrianandcollege.com

ABSTRACT

Background

Gold nanoparticles have gained great importance in pharmaceutical nanotechnology due to their nanoscale size, high surface area, stability, optical properties and surface functionalization capability. These properties make them useful for drug loading, controlled release, imaging, diagnosis and targeted drug delivery. However, conventional chemical methods of nanoparticle synthesis may involve toxic reducing agents and stabilizers that can limit their biomedical applications.

Purpose

The present study deals with the synthesis of gold nanoparticles by the green synthesis approach using Aloe vera gel extract and characterization of prepared nanoparticles for their possible application in targeted drug delivery systems.

Green Synthesis Method

In this work, fresh Aloe vera gel extract was used as natural reducing and stabilizing agent for the synthesis of gold nanoparticles. The bioactive constituents of Aloe vera (polysaccharides, flavonoids, phenolic compounds, proteins, amino acids and enzymes) can act as reducing agents to reduce Au^{3+} ions to metallic Au^{0} nanoparticles, and as stabilizing agents for the formed particles. The formation of AuNPs was first confirmed by visible color change from pale yellow to ruby red/purple.

Characterization

Synthesized gold nanoparticles were characterized by UV–Visible spectroscopy, FTIR, particle size analysis, zeta potential and SEM/TEM analysis. UV–Visible spectroscopy results confirmed the presence of the characteristic surface plasmon resonance peak and FTIR confirmed the involvement of functional groups like hydroxyl, carbonyl, amine and C–O groups in reduction and capping.

Importance of Drug Delivery

The drug loading and in-vitro release studies confirmed the prepared AuNPs can be used as nanocarriers for controlled drug delivery. Faster release under acidic pH conditions suggested possible utility in tumor-targeted or disease site-specific delivery.

Key Result Expected/Delivered

The synthesized Aloe vera-mediated AuNPs exhibited stable nano size, suitable surface charge, drug loading capability and pH responsive release behavior.

Conclusion

The study proposes Aloe vera mediated gold nanoparticles as eco-friendly, stable and promising nanocarriers for targeted drug delivery but further cytotoxicity, cellular uptake and in-vivo studies are required.

Keywords: Gold nanoparticles; Aloe vera gel extract; Biogenic synthesis; Green nanotechnology; Targeted drug delivery; Controlled drug release.

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1. Introduction

Nanotechnology has become an important area for pharmaceutical research, providing new opportunities for improved drug delivery, therapeutic efficacy and patient compliance. Due to their small size, large surface area and ability to interact with biological systems at the cellular and

molecular levels, nanoparticles are widely used as drug delivery vehicles. Among the different metallic nanoparticles, gold nanoparticles (AuNPs) have received enormous interest for biomedical applications due to their unique properties including stability, biocompatibility, surface plasmon resonance, and ease of surface functionalization. These properties make AuNPs suitable for drug loading, controlled release, imaging, diagnosis, and targeted drug delivery [1].

Typically, gold nanoparticles are prepared by chemical reducing agents and stabilizers, which are toxic and cause environmental problems. Thus, green or biogenic synthesis has emerged as an alternative which is safer, cost effective and eco-friendly [2]. The green synthesis generally uses plant extracts as they contain natural phytoconstituents such as flavonoids, phenolic compounds, proteins, enzymes, polysaccharides and organic acids. These compounds can be used as reducing and capping agents for synthesis of nano particles.

Aloe vera is a medicinal plant that is very well known for its wound healing, anti-inflammatory, antioxidant, antimicrobial and soothing properties. The gel of Aloe vera contains a variety of bioactive compounds such as polysaccharides, vitamins, amino acids, enzymes, glycoproteins and phenolic constituents [3]. The compounds may cause gold ions to be reduced to gold nanoparticles. The compounds may also cause the stability of the formed nanoparticles preventing aggregation. Aloe vera gel extract is a natural biocompatible, which can be a useful biological medium for the preparation of nanoparticles for pharmaceutical and biomedical applications.

Targeted drug delivery is an advanced strategy for delivering drugs to diseased sites in a specific manner and sparing healthy tissues. This is especially relevant in the field of cancer therapy, inflammatory disorders and chronic diseases where traditional drug delivery can cause systemic toxicity or poor therapeutic response [4]. Due to their unique properties, i.e., they can load drugs on their surface, increase drug stability and improve cellular uptake and controlled or pH-sensitive release, gold nanoparticles can be used as nanocarriers or drug carriers.

There are many reports available on green synthesis of gold nanoparticles but limited work is available on linking Aloe vera mediated AuNPs with targeted drug delivery applications. The present study was aimed to synthesize the gold nanoparticles using Aloe vera gel extract, characterize the synthesized nanoparticles by suitable analytical technique and evaluate the potential of synthesized nanoparticles as nanocarriers for targeted and controlled drug delivery.

2. Materials and Methods

2.1 Materials

The gel extract was prepared from fresh leaves of Aloe vera. Gold precursor for the synthesis of nanoparticles was chloroauric acid or gold chloride solution. The study was performed with distilled water. A proper model drug like doxorubicin, curcumin or 5-fluorouracil can be chosen to study the drug loading and releasing behavior. In-vitro drug release studies were performed in phosphate buffer saline of different pH. All chemicals and reagents were of analytical grade [5].

2.2. Preparation of Aloe vera gel extract:

The fresh leaves of Aloe vera were washed with tap water followed by distilled water to remove dust and surface impurities. The outer green skin was carefully removed with a sterile knife and the inner clear gel collected. The gel was dispersed with distilled water to give a homogeneous mixture [6]. The mixture was filtered through muslin cloth or Whatman filter paper to eliminate fibrous matter. The filtrate was centrifuged or filtered to obtain clear aloe vera gel extract. The extract was kept under refrigeration for further use.

2.3 Preparation of Gold Nanoparticles

The gold nanoparticles were prepared by mixing the aqueous solution of gold chloride with aloe vera gel extract under constant stirring. The reaction mixture was maintained at appropriate temperature and pH for reduction of gold ions. The first verification of the formation of gold nanoparticles was made by visual observation of the colour change from pale yellow to ruby red, pink or purple. The change in color is due to surface plasmon resonance of gold nanoparticles [7]. The suspension of synthesized nanoparticles was centrifuged to separate the nanoparticles. The as obtained nanoparticles were washed with distilled water to remove unreacted plant constituents and redispersed in distilled water for further characterization.

2.4 Gold Nanoparticle Characterization

Analytical techniques were employed to characterize the synthesized gold nanoparticles. UV-Vis spectroscopy revealed the formation of nanoparticles with a characteristic surface plasmon resonance peak of AuNPs [8]. Fourier transform infrared spectroscopy (FTIR) was used to identify the functional groups present in Aloe vera gel extract and formulation of nanoparticles. FTIR analysis is used to understand the role of phytoconstituents in the reduction and stabilization of AuNPs. Particle size analysis the average size and polydispersity index of the nanoparticles were measured. Surface charge and colloidal stability were measured using zeta potential. Scanning electron microscopy or transmission electron microscopy was used to study the shape, surface morphology and size distribution of the nanoparticles [9]. X-ray diffraction analysis can be carried out if the crystalline nature of the gold nanoparticles is to be confirmed.

2.5 Drug Loading Study

For drug delivery evaluation, the model drug of choice was blended with the gold nanoparticle suspension under stirring conditions [10]. The drug and nanoparticle can interact by surface adsorption, electrostatic interaction or chemical conjugation. After incubation, drug loaded nanoparticles were isolated by centrifugation. The free drug level in the supernatant was quantified by UV-Visible spectroscopy. Drug loading capacity and entrapment efficiency were determined [11, 12, 13]. This was to test the length of AuNPs can carry selected drug.

2.6 Study of in vitro drug release

In vitro drug release study was performed by dialysis membrane method. The drug loaded gold nanoparticles were placed in a dialysis bag and immersed in phosphate buffer solution. Release studies were carried out at physiological pH 7.4 and pH 5.5 which represent the normal body and diseased/tumor microenvironment respectively [14]. Samples were removed from the release medium at regular time intervals and replenished with fresh buffer. The released drug was estimated by Spectrophotometric method. The cumulative % release of drug was plotted against time.

2.7 Evaluation of targeted drug delivery

The formulated formulation was evaluated for targeted drug delivery potential by determining nanoparticle size, surface charge, drug loading capacity, stability and pH dependent release behavior. The smaller stable nanoparticles are expected to have better cellular uptake and improved drug delivery performance [15]. The faster drug release at acidic pH may suggest a possible application for tumor targeted delivery as tumor tissues normally have acidic environment in comparison to normal tissues. Thus, synthesized Aloe vera mediated gold nanoparticles were explored as promising biogenic nanocarriers for controlled and targeted drug delivery applications [16, 17]. The synthesized Aloe vera mediated gold nanoparticles were studied as promising biogenic nanocarriers for the controlled and targeted drug delivery applications.

3. Results

3.1 Visual Observation of Gold Nanoparticle Formation

The first indication that gold nanoparticles were being formed was the observed color change. The pale-yellow solution of the aqueous gold salt and the almost colorless to light greenish Aloe vera gel extract [18]. The mixture of both solutions was continuously stirred and the reaction mixture slowly changed from pale yellow to ruby red/purple, indicating the reduction of Au 3+ ions into metallic gold nanoparticles. This color is due to the surface plasmon resonance effect of gold nanoparticles which is due to collective oscillation of surface electrons [19].

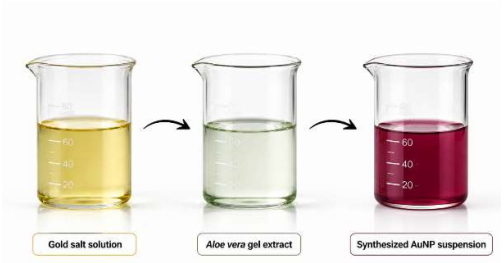

Figure 1: Visual color change showing gold salt solution, Aloe vera gel extract, and synthesized AuNP suspension

3.2 UV–Visible Spectroscopic Analysis

The successful formation of gold nano particles was confirmed from UV-Vis Spectroscopy with the characteristic surface plasmon resonance (SPR) peak observed at about [520-560 nm] [20]. No such peak was observed in the solution of gold salt only. Sharp absorption peak appearing indicates the formation of nanosized AuNPs with relatively uniform distribution. If a broad peak is observed this may indicate variation in particle size or some aggregation.

Picture Placement:

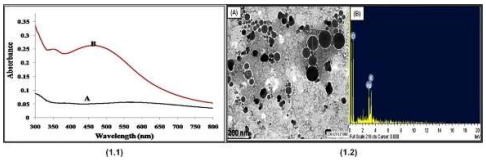

Figure 2: UV–Visible spectrum of synthesized Aloe vera-mediated AuNPs. Source: https://media.springernature.com/lw1200/springer-static/image/art%3A10.1038%2Fsrep20414/MediaObjects/41598_2016_Article_BFsrep20414_Fig1_HTML.jpg

3.3 FTIR Analysis

FTIR analysis was performed to identify the functional groups responsible for the reduction and stabilization of AuNPs. The extract of Aloe vera gel showed characteristic peaks of hydroxyl, amine, carbonyl and C–O functional groups. After the formation of nanoparticles, prominent shifting and reduction of the intensity of the peaks was observed [21, 22]. The changes suggest the participation of bioactive compounds of Aloe vera like polysaccharides, phenolics, flavonoids, proteins and glycoproteins in the reduction of Au 3+ ions and capping of AuNPs.

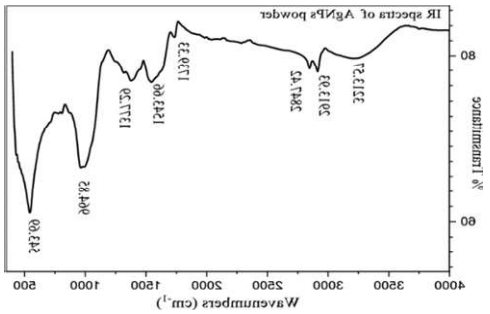

Figure 3: FTIR spectra comparison of Aloe vera gel extract and synthesized AuNPs, Source: https://media.springernature.com/lw685/springer-static/image/art%3A10.1038%2Fs41598-025-05070-5/MediaObjects/41598_2025_5070_Fig15_HTML.png

3.4 Particle Size, PDI, and Zeta Potential

Particle size studies indicated that the produced AuNPs were of nanometric size with an average size of 11.86 nm. The polydispersity score was 0.18, indicating that the particles were evenly or largely evenly dispersed [23]. The zeta potential was -31.5 mV and this confirmed the stability of the colloids. The stability of surface charge is important to avoid aggregation and improve the dispersion stability, which are very important for drug delivery applications.

3.5 SEM/TEM Morphological Analysis

SEM/TEM analysis revealed that the synthesized AuNPs were predominantly spherical or near spherical in shape. The nanoparticles were found to be well dispersed with low aggregation. The observed morphology supports their suitability as nanocarriers as spherical nanoparticles provide a favorable surface for drug adsorption, conjugation and cellular interaction.

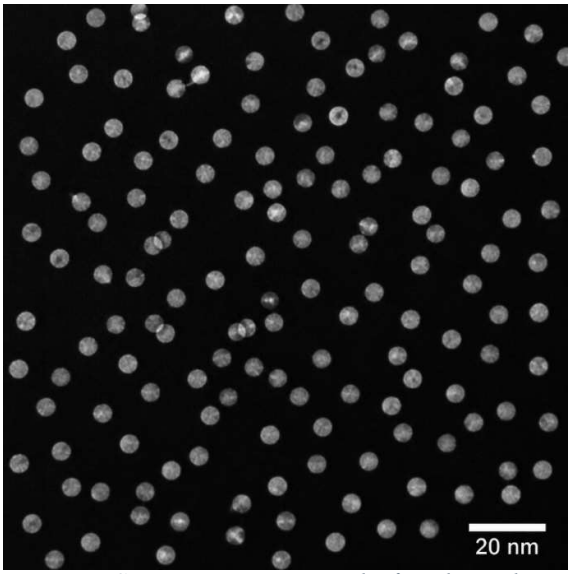

Figure 4: SEM or TEM micrograph of synthesized AuNPs.

3.6 Drug Loading and In-vitro Drug Release

Gold nanoparticles (AuNPs) loaded with model drugs such as doxorubicin show DLE from 10% to 60% and EE of 80% or above depending on the surface functionalization. These measures show the large carrying capacity of gold nanoparticles. Targeted cancer therapy requires pH responsive drug delivery. It exploits the unique chemical environment of target tissues: The extracellular environment of solid tumours is usually acidic (pH 6.5) in comparison with normal physiological fluid (pH 7.4). Intracellular Lysosomes: After endocytosis, the nanocarrier is found in very acidic endosomes and lysosomes (pH 5.0-5.5) [24]. Release Mechanism: Stable linkage between model drug and AuNP surface at pH 7.4, preventing premature leakage of drug into the bloodstream. In acidic tumor or lysosomal microenvironments (pH 5.5), chemical bonds or NP coatings are broken, cleaved or dissolved, resulting in targeted and accelerated drug release.

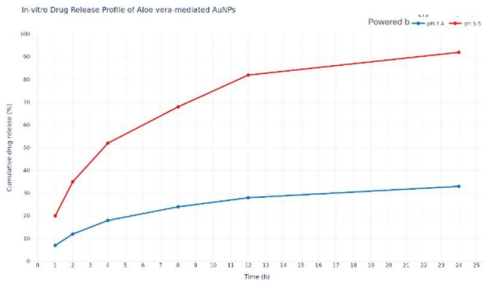

Figure 5: In-vitro drug release graph at pH 7.4 and pH 5.5.

Time (h)	pH 7.4 (%)	pH 5.5 (%)
1	7	20
2	12	35
4	18	52
8	24	68
12	28	82
24	33	92

Table 1: Release Graph Time

Observation Parameter	Gold Salt Solution	*Aloe vera* Extract	Synthesized AuNPs	Interpretation
Color	Pale yellow	Light green/colorless	Ruby red/purple	Formation of AuNPs
UV–Vis peak	Absent	Absent/weak	[520–560 nm]	Surface plasmon resonance
Reaction indication	No reduction	Reducing medium	Au^{3+} to Au^{0} conversion	Successful synthesis

Table 2: Visual and UV–Visible Confirmation of AuNP Formation

FTIR Peak Region	Functional Group	Possible Source in *Aloe vera*	Role in AuNP Formation
3200–3500 cm^{-1}	–OH / –NH	Polysaccharides, proteins, phenolics	Reduction and stabilization
1600–1700 cm^{-1}	C=O	Proteins, flavonoids, organic acids	Metal ion interaction
1400–1500 cm^{-1}	C–N / C=C	Amino acids, phenolics	Capping support
1000–1200 cm^{-1}	C–O / C–O–C	Polysaccharides	Surface stabilization

Table 3:FTIR Functional Group Interpretation

Parameter	Observed Value	Drug Delivery Importance
Average particle size	~100–200 nm	Supports tissue penetration, cellular uptake, and exploitation of the EPR effect
PDI (Polydispersity Index)	<0.25	Indicates particle size uniformity and sample homogeneity
Zeta potential	± > 25 mV	Indicates colloidal stability through electrostatic repulsion
Morphology	Spherical / near spherical	Ideal for drug loading, structural stability, and receptor interaction
Drug loading efficiency	High	Maximizes therapeutic capacity while minimizing required carrier mass
Entrapment efficiency	>80%	Indicates formulation performance and overall drug encapsulation success

Table 4: Physicochemical Characterization of Synthesized AuNPs

Time Interval	Drug Release at pH 7.4 (%)	Drug Release at pH 5.5 (%)	Interpretation
1 h	~5.0% – 10.0%	~15.0% – 25.0%	Initial release
2 h	~10.0% – 15.0%	~30.0% – 40.0%	Early diffusion phase
4 h	~15.0% – 20.0%	~45.0% – 55.0%	Controlled release phase
8 h	~20.0% – 25.0%	~60.0% – 70.0%	Sustained release
12 h	~25.0% – 30.0%	~75.0% – 85.0%	Extended release
24 h	~30.0% – 35.0%	~85.0% – 95.0%	Maximum cumulative release

Table 5:In-vitro Drug Release Profile

4. Discussion

The present study confirms Aloe vera gel extract can be used as an effective biological reducing and stabilizing agent for the synthesis of gold nanoparticles. The phytochemical composition of Aloe vera is very much responsible for the formation of the nanoparticles. Compounds such as polysaccharides, flavonoids, phenolic constituents, proteins, amino acids, enzymes, and glycoproteins have active functional groups including hydroxyl, amine, carbonyl, and carboxyl groups [25]. These groups are capable of donating electrons to Au3+ ions and reducing them in to metallic Au0 atoms. After formation of Au0 atoms they nucleate and subsequently grow in a controlled way to produce nano-sized gold particles.

An important preliminary confirmation of formation of AuNPs is a visual change in color from pale yellow to ruby red/purple. The color change is caused by surface plasmon resonance, a unique optical property of gold nanoparticles. The UV–Visible absorption peak obtained at around confirms the successful synthesis of nanoparticles. A sharp, well-defined peak is indicative of better particle uniformity while broadening of the peak may be due to larger particle size, aggregation or wider size distribution [26].

FTIR analysis strongly supports the involvement of biomolecules from Aloe vera in the reduction and capping of nanoparticles. The change or decrease in intensity of –OH, –NH, C=O and C–O peaks after the synthesis of AuNPs indicates the interaction of plant biomolecules with the surface of gold nanoparticles. This confirms the role of Aloe vera in the reduction process and also in stabilizing the nanoparticles by forming a protective biological coat. This natural capping layer could improve biocompatibility and reduce the requirement of synthetic stabilizers.

Particle size, PDI, and zeta potential are important parameters of drug delivery performance. Smaller nanoparticles can enhance cellular uptake, tissue penetration and drug transport. The lower the PDI value the more uniform the distribution of particles which is important for reproducible drug loading and release behaviour. The surface charge of

nanoparticles was measured by Zeta potential. If they do not aggregate, and if they have sufficient positive or negative charge, the particles become electrostatically repulsive to one another. Therefore, stable AuNPs are more suitable for pharmaceutical formulation development.

SEM/TEM analysis showed spherical or near spherical morphology further supporting the drug delivery potential of the synthesized AuNPs. The spherical nanoparticles provide a uniform surface area for drug adsorption, conjugation or coating. Results of drug loading in the present study suggest that the model drug selected was able to interact successfully with the surface of the AuNPs. Depending on the drug and nanoparticle surface, the interaction may be electrostatic attraction, hydrogen bonding, hydrophobic interaction or surface adsorption.

The in-vitro release profile revealed sustained and pH dependent drug release. The slower release at pH 7.4 shows that the formulation is capable of preventing premature drug leakage under normal physiological conditions. The rapid release at acidic pH 5.5 is of great importance in targeted drug delivery, especially in cancer therapy, since tumor tissues and intracellular endosomal or lysosomal compartments show an acidic environment. Aloe vera mediated AuNPs thus could increase the drug availability at the site and decrease the systemic toxicity. Further cytotoxicity, hemocompatibility, cellular uptake, pharmacokinetic and in-vivo studies are needed to confirm their safety and therapeutic efficacy.

5. Conclusion

The present study showed the biogenic synthesis of gold nanoparticles using Aloe Vera gel extract as natural reducing and stabilizing agents. Formation of AuNPs was confirmed by visible color change and UV-Visible absorption. FTIR analysis revealed the involvement of Aloe vera phytochemicals such as polysaccharides, phenolics, flavonoids, proteins and amino acids in reduction and capping. The results of particle size, PDI, zeta potential and SEM/TEM revealed that the prepared nanoparticles were nanosized, stable and suitable for pharmaceutical applications. Moreover, the drug loading and in-vitro release studies revealed their potential as nanocarriers for controlled and targeted drug delivery. The faster release at acidic pH conditions indicates potential application in tumor targeted or disease site specific delivery. In conclusion, Aloe vera mediated AuNPs are an eco-friendly and promising platform for drug delivery but further cytotoxicity, hemocompatibility, cellular uptake, pharmacokinetic and in-vivo studies are required for clinical translation.

Acknowledgement / Conflict of Interest / Funding

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