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Green Synthesis of Silver Nanoparticles Using Medicinal Plant Extracts and Their Antimicrobial Applications in Topical Formulations

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ABSTRACT

The study examines the synthesis of silver nanoparticles (AgNPs) that are eco-friendly by using medicinal plant extracts and their incorporation in topical antimicrobial preparations. The study has used phytochemicals (alkaloids, flavonoids and tannins) as natural reducing and stabilizing agents, thereby exemplifying a sustainable alternative to the traditional chemical approach which generates stable nanoparticles with increased biocompatibility. AgNPs were synthesized, and their size, stability, crystalline structure, and zeta potential were determined using UV- Vis spectroscopy, analysis of particle size, FTIR and XRD where the AgNPs were found to be nanoscale. The antimicrobial testing showed a high-level Gram-positive and Gram-negative microbes and fungi susceptibility with the Punica granatum-derived nanoparticles exhibiting the strongest inhibitory effect and the lowest MIC values. The introduction of AgNPs in gel preparations produced skin-compatible products with favourable physicochemical qualities (pH, viscosity, spread ability) and high antimicrobial activity, especially Punica granatum-based gels. All in all, the results demonstrate that green-synthesized silver nanoparticles do not only resolve environmental and safety issues but also present a great therapeutic potential in topical use, providing a valuable and viable approach toward further combating microbial infections..

Keywords: *Green Synthesis, Silver Nanoparticles, Medicinal Plant Extracts, Antimicrobial Applications, Topical Formulations.*

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1. INTRODUCTION

Nanotechnology has become one of the most creative and fast-moving scientific disciplines with immense contributions in the fields of medicine, pharmaceuticals and material sciences. Silver nanoparticles (AgNPs) are one of the nanomaterials that have attracted much attention because of their distinct physicochemical characteristics, such as great surface-to-volume ratio, high-catalytic efficiency, and strong antimicrobial properties. AgNPs have conventionally been prepared through physical and chemical synthesis, yet these methods can include the use of toxic reagents and large amounts of energy and non-biodegradable by-products thus limiting their use in biomedical applications. This has seen a paradigm shift in the way nanoparticles are synthesized in a manner that is eco-friendly and sustainable and cost effective.

This is because the green synthesis of silver nanoparticles using extracts of medicinal plants has become a promising substitute to other methods. Phytochemicals derived in plants including alkaloids, flavonoid, tannin, phenols, and terpenoids that can be used as natural reducing and stabilizing agents to enable the transformation of silver ions to stable nanoparticles without using dangerously toxic chemicals. This is a technique that reduces the risks to the environment and, in addition, incorporates the therapeutic effect of the plant metabolites in the nanoparticles thus, augmenting their biological functionality. Furthermore, the application of the medicinal plants offers a dual benefit including the fact that the natural compounds are biocompatible and the silver nanoparticles possess the potent antimicrobial effect which is desired greatly in the field of biomedicine.

The use of plant-mediated AgNPs in the production of topical preparations to treat microbes is one of the most important applications. Bacterial and fungal pathogen-induced skin infections are a significant health issue of concern to the general population, particularly in the time of the increase in antibiotic resistance. Silver nanoparticles have a wide spectrum of antimicrobial effect, disrupting microbial cell membranes, producing reactive oxygen species, and disrupting cellular metabolism. AgNPs can be incorporated into topical preparations (gels, ointments, or creams), which can deliver a concentration to its site of infection, exhibit prolonged release, and increased penetration. Moreover, the simplicity with which green-synthesized AgNPs can be incorporated into topical applications provides safety and reduced toxicity, as well as enhanced patient compliance in relation to chemically synthesized AgNPs.

Thus, the study of green synthesis of silver nanoparticles with the help of medicinal plant extract and their integration into topical antimicrobial preparations has a great potential in the contemporary healthcare. This is not only a way to be in line with the concepts of green chemistry, but a way to deal with the current dire demand of safe, effective, and sustainable antimicrobial treatment. This study aims to fill this gap by demonstrating how eco-friendly AgNPs can be used to treat microbe infections in nanotechnology, phytomedicine and pharmaceutical applications.

1.1. Research objectives

The research objectives of the study are:

To synthesize and characterize silver nanoparticles using medicinal plant extracts.

To evaluate the antimicrobial activity of the synthesized nanoparticles.

To develop and assess topical formulations containing silver nanoparticles for therapeutic use.

2. REVIEW OF LITERATURE

Green synthesis of metal nanoparticles, such as zinc and silver, has demonstrated significantpotential for developing effective antimicrobial topical formulations. These environmentally friendly methods produce stable nanoparticles that exhibit strong inhibitory effects against a variety of skin pathogens while maintaining low toxicity to human cells. Incorporation of these nanoparticles into creams and herbal ointments has been shown to enhance wound healing, tissue regeneration, and overall therapeutic outcomes. The synergy between nanoparticles and plant-based bioactive compounds further improves their efficacy in skin care and infection control. Additionally, plant extracts used in the green synthesis process act as natural reducing and stabilizing agents, enhancing the biocompatibility and safety of these nanoparticles. Studies have highlighted their successful application not only in human medicine but also in veterinary treatments, confirming their broad therapeutic value. Overall, green-synthesized nanoparticles offer a sustainable and innovative alternative to traditional antimicrobial agents, combining environmental benefits with advanced biomedical applications.

3. MATERIALS AND METHODS

The research employed the use of analytical-grade silver nitrate, deionized water, extracts of medicinal plants, and standard formulation excipients to prepare and construct silver nanoparticle-based topical preparations. Due to the green synthesis method, silver nanoparticles were prepared using plant extracts both as reducing agent and stabilizing agent and purified by centrifugation. UV-Visible spectroscopy, dynamic light scattering, zeta potential analysis, electron microscopy, FTIR, and XRD were used to characterize nanoparticles to ascertain their formation, stability and morphology. Against the selected bacterial and fungal strains, antimicrobial activity was measured by the reported techniques including agar well diffusion and MIC assay. Each of the nanoparticles was then implanted into gel and ointment preparations and evaluated with regard to physicochemical, spread ability, and antimicrobial activity, following the tested protocols in the literature.

3.1. Materials

The study used silver nitrate (AgNO 3, analytical grade), deionized water and formulation chemicals (Carbopol 940, propylene glycol, glycerin, triethanolamine, and soft paraffin). Based on reported literature, standard bacterial strains including Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa and the fungal strain Candida albicans were evaluated in antimicrobial testing. Sources of medicine Plant extracts that have been reported to synthesize nanoparticles (e.g., Azadirachtaindica, Ocimum sanctum, or Punica granatum) were selected as reported sources. Published experimental protocols and validated reports provided with information in relation to antimicrobial assays, cytotoxicity and formulation development.

3.2. Green Synthesis of Silver Nanoparticles

To prepare the silver nanoparticles, aqueous silver nitrate solution (1 mM) was mixed with medicinal plant extracts mentioned in the literature to serve as a reducing and stabilising agent. The formation of a typical brownish color was an indication of the formation of nanoparticles. The purification was done by centrifugation and repeated washing with deionized water.

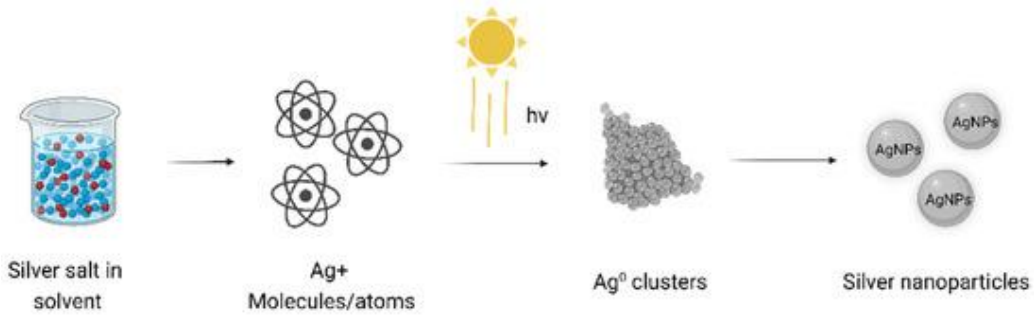

Fig 1: Formation of silver nanoparticles.

3.3. Characterization of Nanoparticles

The produced nanoparticles were characterized by the means of the known techniques. Surface plasmon resonance peaks were confirmed with UV 0 Visible spectroscopy. Dynamic light scattering (DLS) and zeta potential were used to determine particle size and stability. Morphology and size distribution were studied with scanning or transmission electron microscopy (SEM/TEM). Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) were used to identify functional groups involved in the stabilization of nanoparticles and crystalline structure, respectively.

3.4. Antimicrobial Evaluation

Green-synthesized silver nanoparticles were evaluated by the agar well diffusion, broth microdilution assays, which are some of the literature methods that have been used to detect the antimicrobial activity of nanoparticles. The zones of inhibition were compared to selected bacterial and fungi strains and minimum inhibitory concentrations (MICs) were compared with the ones reported in the literature and with standard antibiotics.

3.5. Formulation Development

Silver nanoparticles were used as topical preparations as gels and ointments that were made in accordance with standard formulation preparation. The gels made of Carbopol were neutralized by triethanolamine and combined with the nanoparticles, whereas soft paraffin and liquid paraffin bases were used to make ointments. Parameters of appearance, pH, viscosity, and spread ability, and the reported antimicrobial performance were used to assess the formulations.

4. EXPERIMENTAL ANALYSIS AND RESULTS

The source and stability of the synthesized silver nanoparticles with different medicinal plant extracts were successfully characterized, which displayed nanoscale particle sizes, consistent zeta potentials, and characteristic UV vis absorbance peaks and small particles. The nanoparticles showed a wide-spectrum antimicrobial action against gram positive and gram negative bacterial and fungi as indicated by the zone of inhibition and minimum inhibitory concentration (MIC) of the nanoparticles. Of the extracts, Punica granatum nanoparticles were always more effective antimicrobially potent.

Moreover, addition of these nanoparticles to the topical gel formulations, produced stable and skin compatible products, with good spread properties and increased antimicrobial activity, which points to their therapeutic application.

4.1. Characterization of Silver Nanoparticles

The synthesis of silver nanoparticles by using green synthesis methods in which the medicinal plants extracts serve to catalyze the synthesis of silver nanoparticles was confirmed by UV- Visible spectroscopy, which revealed characteristic surface plasmon resonance peaks. Analysis of the size of the particles indicated that the nanoparticles were in the Nano meter range with constant zeta potential values indicating good colloidal stability. Table 1 gives the most important characterization parameters of silver nanoparticles prepared by the use of various medicinal plant extracts. The parameters are maximum absorption wavelength (λmax) in UV-Visible spectroscopy, average particle size calculated with the help of particle size analysis, zeta potential that signifies the existence of surfaces and stability, and crystalline size identified by X-ray diffraction (XRD). Such measures are vital to the knowledge of the physicochemical characteristics of the nanoparticles, which determine their stability, bioactivity, and possible biomedical formulation.

Table 1:Characterization Parameters of Silver Nanoparticles

Plant Extract	λmax (nm)	Avg. Particle Size (nm)	Zeta Potential (mV)	XRD Crystal Size (nm)
Azadirachtaindica	435	28	-24.5	27
Ocimum sanctum	420	35	-22.1	32
Punica granatum	440	30	-26.3	29
Curcuma longa	415	25	-21.7	24

Table 1 indicated that the synthesized silver nanoparticles had a λmax of between 415 and 440 nm, which proved the synthesis of stable nanoparticles. The extract of Curcuma longa gave the lowest particle size (25 nm) whereas Ocimum sanctum gave slightly bigger particles (35 nm). All the values of zeta potential were negative, between -21.7 mV and -26.3 mV, which may be regarded as evidence of good colloidal stability. XRD sizes were found to be similar to particle size incidences with Curcuma longa exhibiting the lowest crystallite size (24 nm) and Ocimum sanctum the highest (32 nm). In general, P. granatum and C. longa-produced nanoparticles were more preferable in terms of stability and size, rendering them better to use in antimicrobial purposes.

Figure 1 shows the absorbance spectrums of the UV visible and visible ranges of silver nanoparticles developed by the use of various medicinal plant extracts. A popular method of analytical technology that validates the formation of nanoparticles is UV–vis spectroscopy, which detects silver nanoparticles to have a characteristic surface plasmon resonance (SPR) band in the visible region. Particle size, shape and distribution affect the position of the absorbance peak (lmax). This figure offers an insight of the optical properties of the nanoparticles and this tests that they have been synthesized and thus a preliminary indication of the size and stability of the nanoparticles.

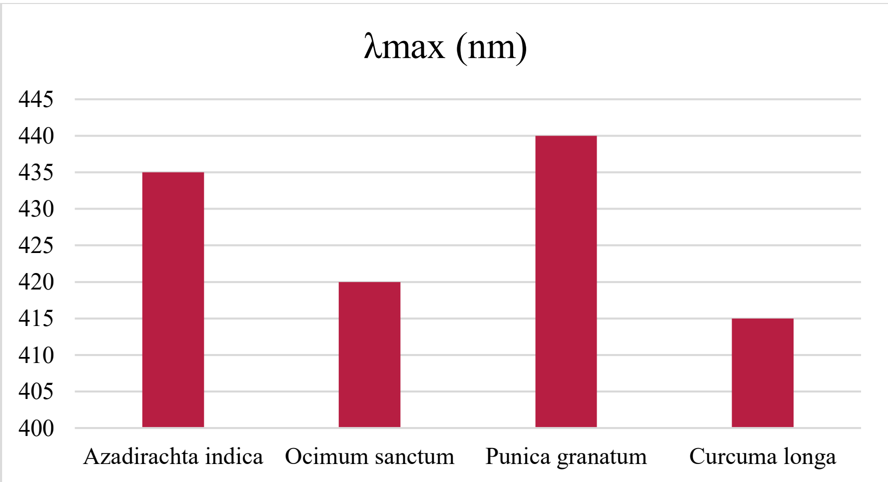

Figure 1: UV–Vis absorbance spectra of synthesized AgNPs

As indicated in Figure 1, the silver nanoparticles synthesized had different λmax values of 415 to 440 nm by different plant extracts. The value of λmax (415 nm) in Curcuma longa was the lowest, which was attributed to the relatively small nanoparticles being formed; whereas in Punica granatum was the highest, indicating a relatively large particle formation. The Azadirachtaindica and Ocimum sanctum showed an intermediate peak absorbance of 435 nm and 420 nm, respectively. These differences show that the phytochemicals found in associated plant extracts are of a critical importance in the nucleation and stabilization of nanoparticles, which directly affects their optical and structural characteristics.

4.2. Antimicrobial Activity Analysis

The synthesized AgNPs antimicrobial activity was determined with Gram-positive and Gram-negative bacteria and fungi. Findings revealed a lot of inhibitory activity, and the difference was based on the plant extracts. Table 2 presents the antimicrobial activity of the green-synthesized silver nanoparticles against some of the microbial strains such as Staphylococcus aureus (Gram-positive), Escherichia coli and Pseudomonas aeruginosa (Gram-negative), and Candida albicans (fungal strain). Antimicrobial effect was determined by agar well diffusion technique in which zone of inhibition is determined in millimetres (mm). The bigger the zone of inhibition, the more powerful is the antimicrobial action, which proves the possibility of the application of silver nanoparticles produced using various plant extracts in the broad-spectrum use as antimicrobials.

Table 2:Zone of Inhibition (mm) of AgNPs against Microbial Strains

Plant Extract	*S. aureus*	*E. coli*	*P. aeruginosa*	*C. albicans*
Azadirachtaindica	19 ± 0.5	21 ± 0.7	16 ± 0.4	18 ± 0.6
Ocimum sanctum	17 ± 0.4	20 ± 0.5	15 ± 0.6	16 ± 0.5
Punica granatum	22 ± 0.6	24 ± 0.8	18 ± 0.7	21 ± 0.6
Curcuma longa	20 ± 0.5	23 ± 0.6	17 ± 0.5	19 ± 0.7

Table 2 shows that the silver nanoparticles synthesized possessed a high antimicrobial activity on all the strains tested; albeit with differing levels because of the plant extract used. Punica granatum nanoparticles demonstrated high zones of inhibition in all strains, 22 mm in S. aureus and 24 mm in E. coli, and it is representative of high antibacterial activity. The curcuma longa showed significant effectiveness as well with 20 mm and 23 mm of inhibitory rings with S. aureus and E. coli respectively. By contrast, Ocimum sanctum was a little less active, especially against P. aeruginosa (15 mm). These findings reveal that although all plant extracts had a positive effect, nanoparticles prepared with Punica granatum showed the strongest and the most uniform antimicrobial effects.

4.3. Minimum Inhibitory Concentration (MIC)

The secondary sources were used to determine MIC values to compare them. Punica granatum nanoparticles exhibited the lowest MIC which was used to depict an increase in antimicrobial effect. Table 3 shows the minimum inhibitory concentration (MIC) of silver nanoparticles made by using various medicinal plant extracts against some microbial strains, such as Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Candida albicans. The lowest concentration of nanoparticles necessary to suppress visible growth of microbes is the MIC, which is a quantitative parameter of antimicrobial efficacy. The information is essential in a comparison of the relative effectiveness of nanoparticles produced with plant sources.

Table 3:Minimum Inhibitory Concentration (MIC, µg/mL) of AgNPs

Plant Extract	*S. aureus*	*E. coli*	*P. aeruginosa*	*C. albicans*
Azadirachtaindica	25	20	40	30
Ocimum sanctum	30	25	42	32
Punica granatum	18	15	28	20
Curcuma longa	22	18	35	25

Table 3 indicates that the value of MIC fluctuated with the plant extract and microbial strain. Silver nanoparticles prepared with Punica granatum had the lowest MIC values in all the microorganisms tested (18 µg/mL against S. aureus and 15 µg/mL against E. coli), implying the highest antimicrobial activity. On the contrary, nanoparticles of Ocimum sanctum presented the greatest MIC values (30-42 ug/mL), which represents a comparatively lower level of efficacy. Intermediate inhibitory activity was exhibited by Azadirachtaindica and Curcuma longa. These results imply that the antimicrobial activity of the nanoparticles produced depends greatly on the phytochemical qualifications of the plant extract.

Figure 2 illustrates the values of MIC of silver nanoparticles with various microbial strains giving a visual representation of antimicrobial activity of silver nanoparticles. The line graph structure can be clearly observed in terms of trends across plant extracts in order to determine which nanoparticles are most effective at low concentrations of inhibiting the growth of microbes.

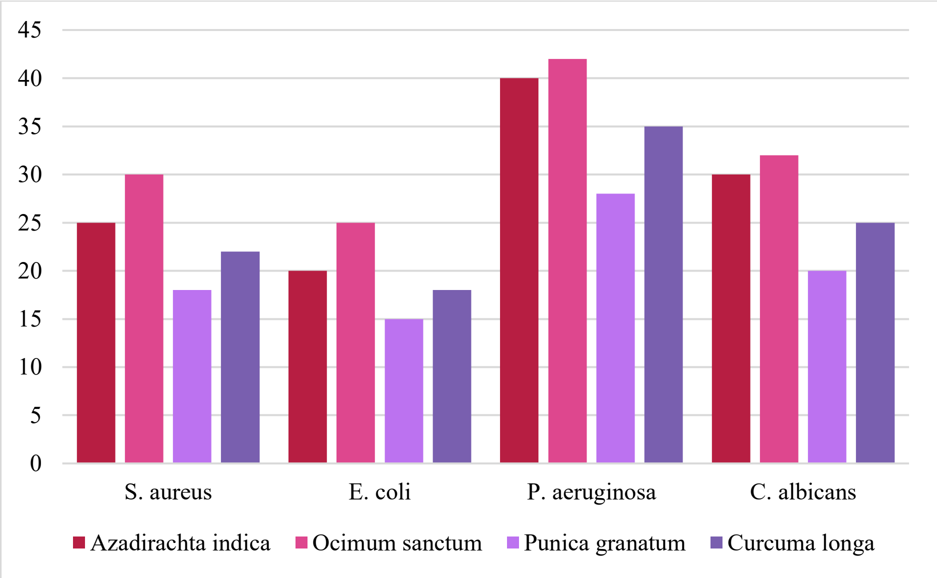

Figure 2: MIC values of AgNPs synthesized from different extracts

Based on Figure 2, it can be observed that nanoparticle synthesized with Punica granatum always needed lower concentrations to suppress the growth of microbes, which supports their high antimicrobial potential. Ocimum sanctum nanoparticles had the smallest concentrations and Azadirachtaindica and Curcuma longa were moderate in MIC. The tabular data is supported by the graphical illustration, which indicates the relative efficiency of the yield of potent antimicrobial nanoparticles by plant-mediated green synthesis.

4.4. Development and Evaluation of Topical Formulations

Silver nanoparticles were added to gel formulations and tested in the area of physicochemical and antimicrobial properties. Table 4 gives a summary of physicochemical characteristics and antimicrobial activity of silver nanoparticles-based topical preparations of various medicinal plant extracts. The most important assessment parameters are appearance, pH, viscosity, ability to spread, and antimicrobial effectiveness (%). These parameters are essential to evaluate the appropriateness of the formulations to be used topically, stability, application easiness, and efficacy in the inhibition of microbial growth. The table gives a relative position of how gel formulations prepared by different plant-mediated nanoparticles have performed.

Table 4:Evaluation Parameters of AgNP-Based Topical Formulations

Formulation Code	Appearance	pH	Viscosity (cP)	Spread ability (cm)	Antimicrobial Efficacy (%)
F1 (*Azadirachta*)	Smooth, greenish	6.4	5500	5.2	82
F2 (*Ocimum*)	Smooth, whitish	6.2	5400	5.1	79
F3 (*Punica*)	Smooth, reddish	6.5	5600	5.3	90
F4 (*Curcuma*)	Smooth, yellowish	6.3	5450	5.0	85

Table 4 demonstrates that all formulations were smooth, with a slight difference in color based on the plant extract added e.g. greenish with Azadirachtaindica and reddish with Punica granatum. The PH was 6.2 to 6.5 and this is within the range of ph that is skin-friendly. The values of viscosity and spread ability point to the fact that both formulations have a good topical application, and Punica granatum formulations are slightly higher in viscosity, as well as spread ability. F3 formulation (Punica granatum) had the greatest antimicrobial activity of 90 percent, F4-85 percent, F1-82 percent, and F2-79 percent, indicating that the F3 extract exhibits the strongest antibacterial outcome when used topically as a gel. The findings herein bring to the fore the effect of the type of plant extracts on the physicochemical characteristics and therapeutic potential of the topical preparations.

The antimicrobial performance of silver nanoparticle-based topical preparations made of various medicinal plant extracts are depicted in figure 3. The antimicrobial effect is designated as a percentage, which is the capability of the formulations in relation to their ability to suppress the growth of microorganisms. The figure presents a visual comparison and it is easy to notice the efficiency of each formulation in terms of delivering the nanoparticles as a form of therapeutic use in topical applications.

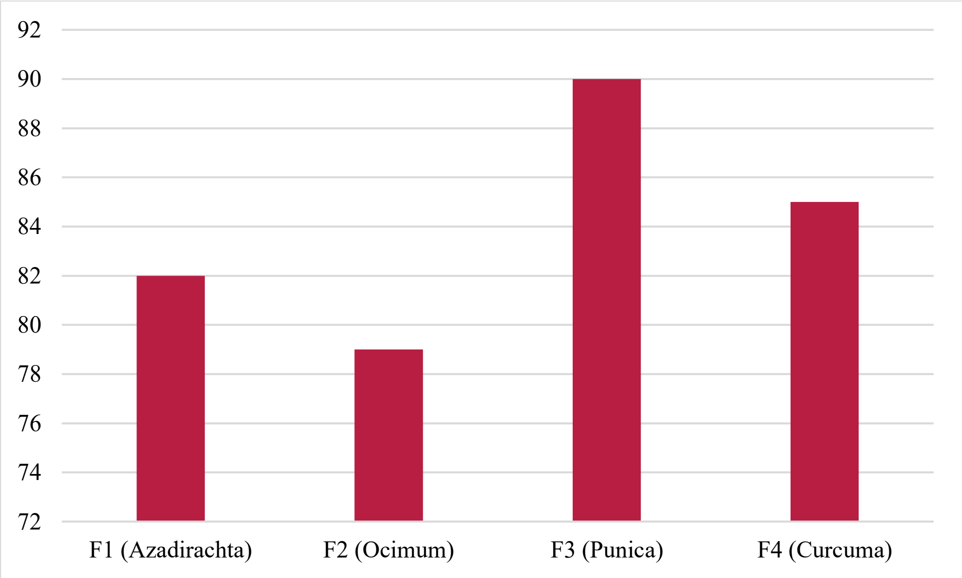

Figure 3:Antimicrobial Efficacy of AgNP topical formulations

Figure 3 revealed that the F3 formulation (Punica granatum) had the greatest antimicrobial effect of 90, which implies that the formulation has the highest capability to prevent microbial growth in comparison with other formulations. F4 formulation (Curcuma longa) had an efficacy of 85% and F1 (Azadirachtaindica) and F2 (Ocimum sanctum) had efficacies of 82 and 79 respectively. These findings indicate that the nature of plant extract employed in the preparation of silver nanoparticles greatly determines the antimicrobial efficacy of the resulting topical preparations, whereby Punica granatum-derived nanoparticles has the greatest potential to produce the best therapeutic effect in a gel-based delivery system.

5. DISCUSSION

It was discussed that the nature of the medicinal plant extract greatly affects the physicochemical properties, stability, and optical characteristics of green-synthesized silver nanoparticles, and smaller and more stable nanoparticles were shown to be produced with extracts such as Curcuma longa. Those differences also influence the efficacy of antimicrobials, with Punica granatum nanoparticles demonstrating higher activity against bacteria and fungi, which is probably caused by synergistic interactions between silver and plant phytochemicals. Topical gel formulations incorporation led to skin-compatible products with good spread-ability and increased antimicrobial activity, whereby it is clear that the choice of plant extract determines the therapeutic outcome of final formulation; in addition to modulating nanoparticle synthesis. Altogether, the research shows that green, plant-based synthesis is an effective and sustainable method of creating efficient antimicrobial treatments.

5.1. Influence of Plant Extracts on Nanoparticle Properties

The selection of medicinal plant extract had a great influence on the physicochemical characteristics of the silver nanoparticles prepared. The differences in particle size, zeta potential, and crystalline structure including that indicated in Table 1 may be explained by the differences in phytochemical makeup of the extracts. Indicatively, Curcuma longa transduced the smallest nanoparticles, probably because of the availability of strong reducing agents, e.g., curcuminoids, that facilitate rapid nucleation. Ocimum pepo, on the contrary, produced comparatively larger nanoparticles implying that the reduction and stabilization process was slower. The negative values of the zeta potential in all the samples denote the presence of the electrostatic stabilization and it can be indicated that plant-derived compounds served as a successful preventive of nanoparticle aggregation. These results highlight the paramount importance of plant metabolites in the regulation of nanoparticles formation and stability.

5.2. Correlation Between Optical Properties and Particle Stability

Nanoparticles formation was confirmed by the presence of typical surface plasmon resonance (SPR) peaks at 415-440nm as identified in the UV-vis spectra (Figure 1). The discrepancies in λmax found in extracts indicate the difference in particle size and state of aggregation. Curcuma longa nanoparticles produced smaller nanoparticles with lower λmax and Punica granatum nanoparticles had higher λmax. This finding confirms the presence of a clear correlation between optical properties and nanoparticles stability, and that to measure nanoparticle quality in green synthesis approaches, SPR analysis can be used as a fast and initial screening technique.

5.3. Antimicrobial Effectiveness and Phytochemical Influence

The antimicrobial test (Tables 2 and 3) revealed that all synthesized nanoparticles had broad-spectrum against Gram-positive and Gram-negative bacteria and fungi. The highest zones of inhibition and lowest MIC values were always recorded with punica granatum nanoparticles, which denotes the highest antimicrobial strength. This increased activity can be explained by the synergistic action of silver nanoparticles and bioactive compounds in the extract which can include polyphenols, tannins and are likely to destabilize the membranes of microbials and cause oxidative stress. The difference in activity of plant extracts indicates the need to choose plant sources to ensure therapeutic benefits are optimized.

5.4. Integration into Topical Formulations

The use of silver nanoparticles in gel preparations led to the stabilization of skin-compatible products with good physicochemical properties (Table 4). Formulations based on Punica granatum had a slightly greater viscosity and spread ability, which could play a role in longer contact with the skin and antimicrobial activity as shown in Figure 3. The measured pH (6.2 and 6.5) is within limits of skin compatibility to provide minimal irritation. The excellent antimicrobial activity of the F3 formulation implies that not only the choice of plant extracts influences the synthesis of nanoparticles but also defines the therapeutic outcome of the ultimate topical product.

5.5. Implications for Sustainable Antimicrobial Therapy

This research shows that silver nanoparticles that have been green-synthesized provide a viable and efficient substitute to those synthesized chemically. Their synthesis is eco-friendly, biocompatible, and with improved antimicrobial activity, which promotes their use in clinical topical therapy. Furthermore, the results indicate the potential of plant-mediated synthesis in manipulating the nanoparticle characteristics to suit certain biomedical use, and in the context of nanotechnology, phytochemistry, and nanotechnology: The application of phytochemicals in elucidating antimicrobial therapy development.

6. CONCLUSION AND RECOMMENDATION

The present study shows that green synthesis of silver nanoparticles (AgNPs) through medicinal plant extracts provides the most economical, environmental-friendly, and efficient alternative to the traditional method of synthesizing silver nanoparticle. The results prove that phytochemicals that are present in plant extracts not only provide the ability to form nanoparticles but also play an important role in the size, stability, and antimicrobial activity of these nanoparticles. Of the extracts tested Punica granatum was found to produce nanoparticles with the highest antimicrobial activity in terms of size, inhibition zone, MIC and performance in topical gel formulations. These formulations had skin-compatible pH, desirable viscosity, smooth texture and high antimicrobial efficacy with up to 90 percent efficacy in Punica granatum-based gels. The general findings reveal the therapeutic potential of incorporating into topical agents' plant-mediated AgNPs in the management of bacterial and fungal infections and especially in a time of increasing antimicrobial resistance. On the basis of the results, the next recommendations are offered:

Future studies are advised to go beyond in vitro studies to in vivo and clinical studies to confirm how safe and therapeutic green-synthesized AgNPs are.

It is critical to develop optimized and reproducible synthesis procedures based on standardized plant extracts in order to assure consistent nanoparticle characteristics and drug consistency.

Extensive long-term biocompatibility and toxicity studies are required in order to assure patient safety and to justify regulatory approval.

Coordination between research centers and pharmaceutical companies should be reinforced in order to scale production, cost reduction and faster clinical translation into market-able antimicrobial products

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