A PROJECT REPORT

ON

GREEN SYNTHESIS OF SILVER NANOPARTICLES USING CARICA PAPAYA LEAVE EXTRACT

BY

NAME

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CERTIFICATION

This is to certify that this project was carried out by NAME with matric no. HND/23/SLT/FT/, submitted to the Department of Science Laboratory Technology, Biochemistry Unit, Institute of Applied Science (IAS), Kwara State Polytechnic, Ilorin, in partial fulfilment for the requirement of the award of Higher National Diploma (HND) in Science Laboratory Technology (SLT).

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ABSTRACT

In this study, we report the green synthesis of silver nanoparticles (AgNPs) using the aqueous leaf extract of Carica papaya, commonly known as bitter leaf. The synthesis process involves the reduction of silver nitrate ($AgNO_3$) by bioactive compounds present in the leaf extract, resulting in the formation of AgNPs. The synthesized nanoparticles were characterized using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) techniques.

FTIR analysis revealed the presence of functional groups such as hydroxyl, aliphatic, aromatic, and amine groups, indicating the involvement of phytochemicals in the reduction and stabilization of AgNPs. SEM images showed that the nanoparticles were predominantly spherical, with a size range of 10-50 nm, and exhibited minimal agglomeration. XRD patterns confirmed the crystalline nature of the AgNPs, with distinct peaks corresponding to the face-centered cubic structure of silver.

The results demonstrate that Vernonia amygdalina leaf extract is an effective bioreductant and stabilizing agent for the green synthesis of silver nanoparticles. This eco-friendly approach not only minimizes the use of hazardous chemicals but also leverages the medicinal properties of the plant, potentially enhancing the antimicrobial and therapeutic applications of the synthesized nanoparticles . The findings of this study contribute to the growing field of green nanotechnology, providing a sustainable alternative for the synthesis of metal nanoparticl

CHAPTER ONE
INTRODUCTION

1.1 Background to the Study

Nanotechnology, the science of synthesizing materials at the nanoscale (1–100 nm), has transformed multiple disciplines, including biomedicine, environmental science, and materials engineering, due to the unique physicochemical properties of nanoparticles (NPs). Silver nanoparticles (AgNPs) are among the most studied nanomaterials, valued for their potent antimicrobial, anticancer, antioxidant, and anti-inflammatory properties (Salem & Fouda, 2021). These properties arise from their high surface-to-volume ratio, which enhances reactivity and interaction with biological systems. However, traditional synthesis methods, such as chemical reduction and physical vapor deposition, rely on toxic reducing agents (e.g., sodium borohydride) and energy-intensive processes, leading to environmental pollution and health risks (Akinsipo et al., 2024). The growing demand for sustainable and eco-friendly alternatives has spurred interest in green synthesis, which utilizes natural resources like plant extracts to reduce and stabilize metal ions into nanoparticles. Green synthesis leverages the rich phytochemical profiles of plants, including phenols, flavonoids, terpenoids, and alkaloids, to serve as both reducing and capping agents, eliminating the need for hazardous chemicals (Pavlova et al., 2024). This approach not only reduces environmental impact but also enhances the biocompatibility of the resulting nanoparticles, making them suitable for biomedical applications. Among various plant sources, Carica papaya (papaya) leaves have gained attention due to their abundance of bioactive compounds, such as papain, carpaine, and polyphenolic compounds, which facilitate the reduction of silver ions (Ag^+) to AgNPs (Devanesan et al., 2021). Carica papaya is a widely available tropical plant, and its leaves are a cost-effective and renewable resource, making it an ideal candidate for scalable green synthesis.

1.2 Properties of Nanoparticles

Nanoparticles exhibit unique properties due to their small size (1–100 nm), high surface area-to-volume ratio, and enhanced reactivity. These properties make AgNPs versatile for applications in drug delivery, wound healing, and cancer therapy.

. These properties include:

i. Optical Properties: Silver nanoparticles display surface plasmon resonance (SPR), resulting in characteristic absorption peaks in the UV-visible spectrum, typically between 400–500 nm, indicating their formation (Jain et al., 2020).

ii. Antimicrobial Activity: AgNPs disrupt bacterial cell membranes, generate reactive oxygen species, and inhibit microbial growth, making them effective against both Gram-positive and Gram-negative bacteria (Pavlova et al., 2024).

iii. Biocompatibility: Green-synthesized AgNPs, capped with plant-derived biomolecules, exhibit lower cytotoxicity compared to chemically synthesized nanoparticles, enhancing their suitability for biomedical applications (Purwaningsih & Indrayudha, 2024).

iv. Stability: The zeta potential of CPL-AgNPs, often around -15.58 mV, indicates good colloidal stability due to electrostatic repulsion (Jain et al., 2020).

1.3 Classification of Nanoparticles

Nanoparticles can be classified based on their origin, composition, and structure:

1.3.1 Based on Origin:

Classifying nanoparticles by origin helps distinguish between naturally occurring and human-engineered particles, which impacts their properties, applications, and safety profiles. Natural nanoparticles are often biocompatible but less controllable, while synthetic ones are tailored for specific functions.

1.3.1.1 Natural Nanoparticles:

These occur in biological or environmental systems and are studied to understand natural processes or mimic them in applications. Examples include: Volcanic Ash in which Nano-sized ash particles from volcanic eruptions can affect air quality and climate, Viruses in which naturally occurring nanoparticles (e.g., adenovirus, ~70-90 nm) are studied for gene delivery, also, Ferritin which is a protein nanoparticle (~12 nm) that stores iron in biological systems.

1.3.1.2 Synthetic Nanoparticles:

Engineered for precise control over size, shape, and properties, enabling applications in technology and medicine. Examples are Quantum Dots Semiconductor nanoparticles (e.g., CdSe, ~2-10 nm) used in displays and bioimaging, Carbon Nanotubes Cylindrical carbon structures (~1-2 nm diameter) used in electronics and composites, Gold Nanoparticles Synthesized for drug delivery and cancer therapy (~5-50 nm).

1.3.2 Based on Composition:

Composition determines chemical and physical properties, such as reactivity, toxicity, and functionality, guiding their use in specific applications.

1.3.2.1 Organic Nanoparticles

Biocompatible and often biodegradable, making them ideal for biomedical applications like drug delivery. Examples include Liposomes- Lipid vesicles (~50-200 nm) used to encapsulate drugs (e.g., Doxil for cancer treatment), Dendrimers- Branched polymers (~1-10 nm) for targeted drug delivery (e.g., PAMAM dendrimers). Polymeric Nanoparticles- PLGA nanoparticles (~100-200 nm) for controlled drug release.

1.3.2.2 Inorganic Nanoparticles

Offer unique optical, magnetic, or electrical properties for applications in catalysis, imaging, and electronics. Examples include Gold Nanoparticles-Used in photothermal therapy and diagnostics (~10-50 nm), Titanium Dioxide (TiO_2)-Nanoparticles (~20-100 nm) used in sunscreens and photocatalysis, Quantum Dots-CdSe or ZnS nanoparticles (~2-10 nm) for fluorescence imaging.

1.3.2.3 Carbon-Based Nanoparticles

Exceptional mechanical, electrical, and thermal properties make them suitable for nanotechnology and materials science. Examples are Fullerenes- C60 molecules (~1 nm) used in drug delivery and antioxidants, Graphene- Single-layer carbon sheets (~0.34 nm thick) for flexible electronics, Carbon Nanotubes- Single- or multi-walled tubes (~1-50 nm diameter) for composites.

1.3.2.4 Hybrid Nanoparticles

Combine advantages of organic and inorganic materials for multifunctional applications. Examples include Lipid-Coated Quantum Dots: Used for combined imaging and drug delivery, Silica-Coated

Gold Nanoparticles: Enhance stability and biocompatibility for biosensing.

1.3.3 Based on Structure:

Structure influences stability, interaction with environments, and functionality, tailoring nanoparticles for specific roles.

1.3.4 Core-Shell Nanoparticles:

Core provides primary function (e.g., optical), while shell enhances stability or biocompatibility. Examples are; Silica-Coated Gold Nanoparticles; Silica shell improves stability for biosensing (~20-100 nm), $Fe_3O_4@SiO_2$ Nanoparticles; Magnetic core with silica shell for MRI and drug delivery.

1.3.3.2 Composite Nanoparticles

Combine properties of different materials for enhanced performance. Examples include; Polymer-Metal Hybrids; PLGA-gold composites for imaging and therapy, Carbon-Metal Composites, Graphene-gold nanoparticles for sensors.

1.3.3.3 Hollow Nanoparticles

Hollow interiors allow drug loading or lightweight structures. Examples are; Hollow Gold Nanoshells- Used in photothermal cancer therapy (~50-150 nm), Nanocages- Gold nanocages for drug release triggered by light.

1.4 Methods of Synthesizing Nanoparticles

Nanoparticle synthesis methods are broadly categorized into botton-up and botton-down approaches, with green synthesis being a subset of the botton-up method.

1.4.1 Botton-Up

The botton-up approach involves building nanoparticles from atoms or molecules through chemical or biological processes. Green synthesis, a botton-up method, uses plant extracts or microorganisms to reduce metal ions into nanoparticles. In the case of CPL-AgNPs, phytochemicals in Carica papaya leaf extract reduce Ag^+ ions from silver nitrate ($AgNO_3$) to Ag^0, forming stable nanoparticles (Jain et al., 2020). This method is eco-friendly, cost-effective, and avoids toxic chemicals, making it suitable for biomedical applications (Pavlova et al., 2024). Additionally, green synthesis can be tailored by adjusting parameters like pH, temperature, and extract concentration to control particle size and morphology, further optimizing their functionality for specific applications.

1.4.2 Top-Down

The top-down approach, in contrast, involves breaking down bulk materials into nanoparticles through physical methods such as mechanical milling, laser ablation, or nanolithography. These techniques offer high precision in shaping nanoparticles but are often energy-intensive and require sophisticated equipment, increasing operational costs. Mechanical milling, for example, uses high-energy ball mills to grind bulk materials into nanoscale particles, but it may result in irregular particle sizes and shapes due to uneven mechanical forces (Jain et al., 2020). Laser ablation, another top-down method, employs high-energy laser pulses to vaporize material from a solid surface, producing nanoparticles with controlled properties; however, it demands precise calibration to avoid defects. Similarly, nanolithography enables intricate patterning at the nanoscale but is limited by high costs and complexity, making it less scalable for large-scale production. These drawbacks, combined with the potential for contamination from grinding media or equipment, restrict the applicability of top-down methods in green nanotechnology, where sustainability and biocompatibility are priorities (Pavlova et al., 2024).

1.4.1 Green Synthesis of Nanoparticles

Green synthesis is an eco-friendly, low-cost, and sustainable alternative to traditional physical and chemical nanoparticle synthesis methods. Unlike chemical synthesis, green synthesis avoids toxic reagents and hazardous byproducts (Verma et al., 2020). It leverages biological systems primarily plant extracts to reduce metal salts into nanoparticles. The phytochemicals in these extracts act as reducing, capping, and stabilizing agents (Khan et al., 2022).

Green synthesis of nanoparticles employs biological agents such as plant extracts, fungi, bacteria, or algae to produce nanomaterials in an environmentally benign manner. This approach contrasts with conventional methods, which often involve toxic chemicals, high temperatures, and significant energy consumption, leading to environmental and health concerns (Jain et al., 2020). In the synthesis of silver nanoparticles, plant extracts like Carica papaya leaf extract (CPLE) are mixed with a silver nitrate solution, where phytochemicals reduce Ag^+ to Ag^0, resulting in nanoparticles with a characteristic reddish-brown color due to surface plasmon resonance (SPR) peaks at 400–450 nm (Pavlova et al., 2024).

The green synthesis process offers multiple advantages: it is cost-effective, reduces environmental toxicity, and produces nanoparticles with enhanced biocompatibility due to the natural capping of biomolecules (Singh et al., 2020). For instance, CPLE-AgNPs exhibit a zeta potential of approximately -15.58 mV, indicating good colloidal stability due to electrostatic repulsion mediated by phytochemical coatings (Jain et al., 2020). Recent advancements have focused on optimizing synthesis parameters such as pH (optimal at 6–8), temperature (25–50°C), and extract-to-metal ion ratio using statistical tools like response surface methodology to improve nanoparticle yield and uniformity (Pavlova et al., 2024).

Applications of green-synthesized AgNPs are diverse, spanning antimicrobial coatings, cancer therapy, and environmental remediation. For example, CPLE-AgNPs have shown strong antibacterial activity against multidrug-resistant pathogens like Escherichia coli and Staphylococcus aureus, addressing global challenges like antimicrobial resistance (Pavlova et al., 2024). However, limitations such as potential phytotoxicity and the need for precise control over nanoparticle size and shape necessitate further investigation. Emerging research also explores the integration of green-synthesized AgNPs into nanocomposites for enhanced functionality, such as in water purification systems (Jain et al., 2020). The scalability and reproducibility of green synthesis make it a cornerstone of sustainable nanotechnology.

1.4.1.1 Hydrothermal Synthesis

Hydrothermal synthesis has been widely used since the 1970s for producing metal oxide nanoparticles (e.g., TiO_2, ZnO) and other nanomaterials under high-pressure and high-temperature aqueous conditions. Recent studies have explored its use for synthesizing silver nanoparticles (AgNPs) and other metallic nanoparticles with controlled morphology (Byrappa & Adschiri, 2007). It has been applied in fields like photocatalysis and energy storage (Wang et al., 2019).

Hydrothermal synthesis involves heating aqueous solutions of metal salts in a sealed vessel (autoclave) at temperatures typically between 100–250°C and pressures above 1 atm. The process promotes nucleation and growth of nanoparticles through controlled chemical reactions in a supercritical or subcritical water environment. Parameters like temperature, pressure, and precursor concentration dictate particle size and morphology.

Advantages:

i. Produces highly crystalline nanoparticles with precise control over size and shape.
ii. Suitable for a wide range of materials, including oxides, sulfides, and metals.
iii. Can incorporate green principles by using water as a solvent, reducing the need for toxic organic solvents.
iv. Scalable for industrial applications.

Disadvantages:

i. Requires high-pressure equipment, increasing operational costs and safety concerns.
ii. Energy-intensive due to elevated temperatures.
iii. Limited to materials stable under aqueous conditions.
iv. Longer reaction times compared to some methods (hours to days).

1.4.1.2 Sol-Gel Synthesis

The sol-gel method, developed in the 1980s, is a versatile technique for synthesizing metal oxide nanoparticles (e.g., SiO_2, TiO_2) and hybrid nanomaterials. It has been used to produce AgNPs embedded in silica matrices for antimicrobial applications (Rahman et al., 2021). Recent advances focus on incorporating bio-based precursors to align with green synthesis principles (Niederberger & Pinna, 2009).

The sol-gel process involves the transition of a solution (sol) of metal alkoxides or salts into a gel through hydrolysis and condensation reactions, followed by drying and calcination to form nanoparticles. The process occurs at relatively low temperatures (25–100°C) and allows for the incorporation of dopants or biological capping agents.

Advantages:

i. Offers excellent control over nanoparticle composition, size, and porosity.
ii. Low-temperature processing reduces energy consumption.
iii. Produces highly pure and uniform nanoparticles.

iv. Compatible with green synthesis when using bio-based precursors or aqueous systems.

Disadvantages:

i. Often requires toxic organic solvents (e.g., ethanol, alkoxides), conflicting with green synthesis goals.
ii. Long processing times due to gelation and drying stages.
iii. Calcination may release volatile organic compounds, posing environmental concerns.
iv. Scaling up can be challenging due to gel stability issues.

1.4.1.3 Chemical Precipitation

Chemical precipitation is a well-established method for synthesizing AgNPs and other metal nanoparticles, dating back to early colloidal chemistry studies. It has been used to produce AgNPs for antimicrobial coatings and catalysis (Sun et al., 2018). Recent work explores greener precipitants, such as plant-derived reducing agents, to minimize toxicity (Verma et al., 2020).

Chemical precipitation involves the rapid addition of a precipitating agent to a metal salt solution, causing the formation of insoluble nanoparticles. Reducing agents (e.g., sodium borohydride) and stabilizers (e.g., PVP) are often used to control particle size and prevent aggregation. The process occurs at ambient or slightly elevated temperatures.

Advantages:

i. Simple, cost-effective, and rapid process.
ii. Easily scalable for large-scale production.
iii. Allows precise control over particle size by adjusting reagent concentrations and pH.
iv. Can be adapted for green synthesis using plant extracts or biocompatible stabilizers.

Disadvantages:

i. Often relies on toxic reducing agents (e.g., hydrazine), generating hazardous byproducts.

ii. Poor control over nanoparticle shape compared to other methods.
iii. Potential for aggregation without effective stabilizers.
iv. Environmental concerns due to chemical waste disposal.

1.4.1.4 Electrodeposition

Electrodeposition has been used since the 1990s to synthesize metallic nanoparticles (e.g., Ag, Au) on conductive substrates for applications in electronics and sensors. Recent studies have explored its use for AgNPs in antimicrobial coatings and electrocatalysis (Zhang et al., 2020). Efforts are underway to integrate bio-based electrolytes for greener processes.

Electrodeposition involves the reduction of metal ions from an electrolyte solution onto a cathode via an applied electric current. The process occurs at room temperature, with particle size and morphology controlled by parameters like current density, voltage, and electrolyte composition.

Advantages:

i. Precise control over nanoparticle deposition and morphology.
ii. Room-temperature process, reducing energy consumption.
iii. Direct deposition onto substrates, ideal for coatings and device fabrication.
iv. Can be adapted for green synthesis using non-toxic electrolytes.

Disadvantages:

i. Requires conductive substrates, limiting material versatility.
ii. Electrolyte solutions may contain toxic chemicals, posing environmental risks.
iii. Scaling up is complex and costly due to equipment requirements.
iv. Limited to thin films or surface-bound nanoparticles.

1.4.1.5 Microwave-Assisted Synthesis

Microwave-assisted synthesis emerged in the 2000s as a rapid method for producing AgNPs and other nanomaterials. It has been applied in biomedical and catalytic applications due to its speed and efficiency (Tsuji et al., 2019). Recent studies explore microwave-assisted green synthesis using plant extracts as reducing agents (Pavlova et al., 2024).

Microwave irradiation rapidly heats a solution containing metal salts and reducing agents, promoting nucleation and growth of nanoparticles. The uniform heating enhances reaction kinetics, producing nanoparticles in minutes. Parameters like microwave power, irradiation time, and precursor concentration control particle size.

Advantages:

i. Extremely fast reaction times (minutes vs. hours).
ii. Uniform heating leads to consistent nanoparticle size and morphology.
iii. Energy-efficient compared to hydrothermal methods.
iv. Compatible with green synthesis when using plant extracts or aqueous systems.

Disadvantages:

i. Requires specialized microwave equipment, increasing costs.
ii. Limited control over complex nanoparticle shapes.
iii. Potential for uneven heating in large-scale setups.
iv. Safety concerns due to microwave radiation exposure.

1.4.1.6 Template-Assisted Synthesis

Template-assisted synthesis has been used since the 1990s to produce nanostructured materials with controlled shapes, such as nanorods and nanotubes. It has been applied to synthesize AgNPs for optical and biomedical applications (Hulteen & Martin, 1997). Recent work focuses on bio-based templates (e.g., cellulose) for greener approaches (Jain et al., 2020).

This method uses a template (e.g., porous membranes, micelles, or biomolecules) to direct the growth of nanoparticles. Metal ions are reduced or deposited within the template's confined spaces, defining the nanoparticle's size and shape. The template is later removed or retained, depending on the application.

Advantages:

Exceptional control over nanoparticle size, shape, and alignment.

Produces complex nanostructures (e.g., nanorods, hollow spheres).

Compatible with green synthesis when using bio-based templates (e.g., plant-derived polymers).

Versatile for various materials, including metals and oxides.

Disadvantages:

Template removal often requires harsh chemicals or high temperatures, negating green synthesis benefits.

Complex and time-consuming process, limiting scalability.

High cost of templates and processing steps.

Potential for template contamination in final product.

1.4.4 Carica papaya

Carica papaya is a tropical plant native to Mexico and Central America, now cultivated globally. Its leaves are rich in bioactive compounds, including carpaine, flavonoids, and proteolytic enzymes, which facilitate the reduction and stabilization of AgNPs (Purwaningsih & Indrayudha, 2024). The synthesis process involves mixing leaf extract with $AgNO_3$ solution, leading to a color change from light yellow to reddish-brown, indicating nanoparticle formation due to SPR (Jain et al., 2020). CPL-AgNPs have shown promising antimicrobial activity against pathogens like Escherichia coli and Staphylococcus aureus, as well as potential in treating oral diseases (Pavlova et al., 2024).

1.4.5 Taxonomy

Carica papaya belongs to the following taxonomic classification:

- Kingdom: Plantae
- Phylum: Tracheophyta
- Class: Magnoliopsida
- Order: Brassicales
- Family: Caricaceae
- Genus: Carica
- Species: Caricapapaya

This classification underscores its botanical significance and its role as a source of phytochemicals for nanoparticle synthesis (Jain et al., 2020).

1.6 Statement of the Problem

The synthesis of silver nanoparticles (AgNPs) using conventional chemical and physical methods poses significant environmental and health challenges due to the use of toxic reducing agents, such as sodium borohydride and hydrazine, and energy-intensive processes like high-temperature annealing or laser ablation (Salem & Fouda, 2021). These methods generate hazardous byproducts, contribute to environmental pollution, and often require costly purification steps, limiting their scalability and sustainability. Additionally, chemically synthesized AgNPs may exhibit reduced biocompatibility due to residual toxic chemicals on their surface, restricting their use in biomedical applications such as drug delivery or wound healing (Akinsipo et al., 2024).

Green synthesis, utilizing plant extracts like Carica papaya leaf extract, offers a promising alternative by reducing environmental impact and enhancing biocompatibility. However, despite its potential, several challenges remain. The variability in phytochemical composition of Carica papaya leaves, influenced by factors such as plant age, geographical location, and seasonal changes, can lead to inconsistencies in nanoparticle size, shape, and stability, affecting reproducibility (Pavlova et al., 2024).

Moreover, the application of Carica papaya-mediated AgNPs against specific pathogens, such as oral bacteria (Streptococcus spp.) responsible for dental caries, and cancer cell lines (e.g., MCF-7 and HepG2) remains underexplored. Existing studies often focus on general antimicrobial activity without addressing specific mechanisms, such as membrane disruption or reactive oxygen species (ROS) generation, or evaluating long-term stability and cytotoxicity in relevant biological models (Pavlova et al., 2024).

1.7 Aim and Objectives of the Study

The aim of this study is to synthesize and characterize sliver nanoparticle from carica papaya leaf extract. The following are the objectives of the study:

i. To synthesize silver nanoparticles using Carica papaya leaf extract via a green synthesis approach.
ii. To characterize the synthesized AgNPs using UV-Vis, FTIR, XRD, SEM, and TEM.

1.8 Significance of the Study

This study makes a significant contribution to the field of sustainable nanotechnology by demonstrating the efficacy of Carica papaya leaf extract as a green reducing and stabilizing agent in the synthesis of silver nanoparticles (AgNPs). The use of plant-based extracts offers a cost-effective, eco-friendly, and non-toxic alternative to conventional chemical synthesis methods, which often rely on hazardous reagents and energy-intensive processes. By leveraging the bioactive compounds in Carica papaya leaves, such as flavonoids, alkaloids, and phenolic compounds, this research showcases a scalable and environmentally benign approach to nanoparticle production, aligning with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) (Akinsipo et al., 2024).

The findings of this study have far-reaching implications for both dentistry and oncology. In dentistry, the synthesized AgNPs exhibit potent antimicrobial properties, making them promising candidates for applications in dental materials, such as coatings for dental implants, restorative composites, and root canal disinfectants. These nanoparticles can combat oral pathogens like Streptococcus mutans and Candida albicans, which are responsible for dental caries and oral infections, thereby improving oral health outcomes. In oncology, the AgNPs demonstrate potential as therapeutic agents due to their cytotoxic effects on cancer cells, attributed to their ability to induce oxidative stress and apoptosis. This opens avenues for developing targeted drug delivery systems and photothermal therapies for cancers such as breast, lung, or cervical cancer, offering less invasive alternatives to conventional treatments.

Beyond these applications, the study addresses critical challenges in nanotechnology, including scalability, cost, and environmental impact. Traditional AgNP synthesis methods often involve toxic chemicals like sodium borohydride or hydrazine, which pose risks to human health and the environment. In contrast, the use of Carica papaya leaf extract utilizes renewable, biodegradable resources, reducing the ecological footprint of nanoparticle production. This approach also supports local economies in regions where Carica papaya is abundant, such as tropical and subtropical areas, by providing a value-added application for an underutilized agricultural resource.

Furthermore, this research contributes to the growing body of knowledge on green nanotechnology by providing a reproducible and efficient synthesis protocol. The characterization of the resulting AgNPs, including their size, shape, and stability, offers valuable insights for optimizing their performance in biomedical applications. The study also sets a foundation for future research into other plant-based extracts and their potential in synthesizing multifunctional nanoparticles, fostering innovation in sustainable materials science.

By bridging the gap between green chemistry and biomedical applications, this study not only advances scientific understanding but also promotes practical solutions for healthcare challenges. The eco-friendly synthesis of AgNPs using Carica papaya leaf extract has the potential to reduce reliance on costly and environmentally harmful methods, paving the way for sustainable nanotechnology innovations that benefit both human health and the planet (Akinsipo et al., 2024).

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CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Nanotechnology and Green Synthesis

Nanotechnology involves the design, synthesis, and application of materials at the nanoscale (1–100 nm), where unique properties such as enhanced surface area, quantum effects, and high reactivity emerge. Silver nanoparticles (AgNPs) are particularly significant due to their applications in biomedicine, catalysis, and environmental remediation (Salem & Fouda, 2021). Conventional synthesis methods, including chemical reduction, sol-gel processes, and physical vapor deposition, often rely on toxic chemicals and high-energy inputs, leading to environmental concerns and limiting their use in sensitive applications like drug delivery (Akinsipo et al., 2024). Green synthesis, utilizing biological agents such as plant extracts, microorganisms, or enzymes, has emerged as a sustainable alternative. Plant-mediated synthesis is particularly advantageous due to its simplicity, cost-effectiveness, and the presence of phytochemicals that act as reducing, capping, and stabilizing agents, eliminating the need for hazardous chemicals (Pavlova et al., 2024).

The mechanism of green synthesis involves the reduction of silver ions (Ag^+) to metallic silver (Ag^0) by phytochemicals such as phenols, flavonoids, and alkaloids, which donate electrons to facilitate the reduction process. These compounds also form a capping layer around the nanoparticles, preventing aggregation and enhancing stability (Devanesan et al., 2021). Recent studies have elucidated the role of specific functional groups, such as hydroxyl (-OH) and carbonyl (C=O), in stabilizing AgNPs, as confirmed by FTIR analysis (Pavlova et al., 2024). Compared to microbial synthesis, which requires complex culturing conditions, plant-based synthesis is faster and more scalable, making it suitable for industrial applications (Salem & Fouda, 2021).

2.2 Carica papaya as a Source for Green Synthesis

Carica papaya (papaya), a tropical plant widely cultivated for its fruit, has leaves rich in bioactive compounds, including flavonoids, phenolic acids, alkaloids (e.g., carpaine), and enzymes (e.g., papain), which are effective in reducing silver ions and stabilizing AgNPs (Devanesan et al., 2021). The leaves are abundant, renewable, and easily accessible, making them a cost-effective resource for green synthesis. Studies have shown that Carica papaya leaf extract produces AgNPs with sizes ranging from 10–50 nm, exhibiting a characteristic surface plasmon resonance (SPR) peak at 420–470 nm, indicative of nanoparticle formation (Pavlova et al., 2024). The phytochemicals in the extract, particularly flavonoids and phenols, interact with silver ions through their functional groups, reducing Ag^+ to Ag^0 and forming a protective coating that enhances nanoparticle stability (Akinsipo et al., 2024).

Carica papaya, a perennial plant native to Central America and widely cultivated in tropical regions, has gained significant attention as a sustainable source for green synthesis of silver nanoparticles (AgNPs) due to its abundant phytochemicals and environmental compatibility. The leaves of Carica papaya are particularly effective, serving as a natural reservoir of bioactive compounds such as flavonoids, phenolic acids, alkaloids, and enzymes, which act as both reducing and capping agents during nanoparticle synthesis (Jain et al., 2020). These compounds reduce silver ions (Ag^+) from silver nitrate ($AgNO_3$) to metallic silver (Ag^0), forming stable, spherical nanoparticles typically ranging from 10 to 70 nm in size (Singh et al., 2020).

The use of Carica papaya in green synthesis is advantageous due to its widespread availability, low cost, and non-toxic nature compared to chemical reducing agents like sodium borohydride. The plant's biocompatibility further enhances the suitability of CPLE-AgNPs for biomedical applications, such as wound dressings and targeted drug delivery (Purwaningsih & Indrayudha, 2024). Moreover, the eco-friendly nature of CPLE eliminates the need for hazardous solvents, aligning with global sustainability goals. However, challenges such as batch-to-batch variability in phytochemical content and the need for standardized extraction protocols remain areas for further research (Jain et al., 2020). These attributes position Carica papaya as a promising candidate for scalable, green nanotechnology applications.

Comparative studies have evaluated Carica papaya against other plant extracts, such as Azadirachta indica (neem) and Moringa oleifera, for AgNP synthesis. While neem-mediated AgNPs show strong antimicrobial activity, Carica papaya-mediated AgNPs exhibit superior anticancer activity due to their smaller size and higher phenolic content (Devanesan et al., 2021). Additionally, Carica papaya leaves are less sensitive to seasonal variations compared to other plants, ensuring consistent phytochemical profiles for reproducible synthesis (Pavlova et al., 2024). However, challenges remain in standardizing extract preparation to minimize variability in nanoparticle properties, as noted in recent reviews (Salem & Fouda, 2021).

2.3 Phytochemistry of Carica papaya

Carica papaya is rich in a variety of bioactive compounds, including phenolic acids, flavonoids, alkaloids, saponins, and terpenoids, all of which are known to play significant roles in nanoparticle synthesis (Oladele et al., 2021). The antioxidant and electron-donating capabilities of these compounds enable the reduction of Ag^+ ions to metallic Ag^0. Moreover, they stabilize the nanoparticles by forming a capping layer that prevents aggregation.

According to Abubakar et al. (2022), the leaves of C. papaya exhibit significant antimicrobial and antioxidant activity, suggesting the presence of potent biomolecules that can be exploited for nanoparticle synthesis.

The phytochemical composition of Carica papaya leaves underpins their efficacy in green nanoparticle synthesis. The leaves contain a diverse array of bioactive compounds, including flavonoids, phenolic acids, alkaloids (e.g., carpaine), terpenoids, saponins, and proteolytic enzymes like papain, which collectively contribute to the reduction, stabilization, and functionalization of AgNPs (Jain et al., 2020). Flavonoids and phenolic compounds, rich in hydroxyl groups, serve as primary reducing agents by donating electrons to Ag^+ ions, facilitating the formation of Ag^0 nanoparticles (Pavlova et al., 2024). These compounds also act as capping agents, coating the nanoparticle surface to prevent aggregation and enhance stability (Singh et al., 2020).

Gas chromatography-mass spectrometry (GC-MS) analyses have identified over 20 bioactive compounds in Carica papaya leaf extract, including quercetin, kaempferol, and caffeic acid, which contribute to the antioxidant and antimicrobial properties of CPLE-AgNPs (Purwaningsih & Indrayudha, 2024). Alkaloids like carpaine enhance the nanoparticles' bioactivity, making them effective against pathogens and cancer cells. For instance, CPLE-AgNPs have demonstrated significant cytotoxicity against prostate cancer cells by generating reactive oxygen species (ROS) and inducing apoptosis (Singh et al., 2020). The enzyme papain, a cysteine protease, not only aids in reduction but also improves the biocompatibility of nanoparticles, reducing cytotoxicity to non-target cells (Purwaningsih & Indrayudha, 2024).

The phytochemical profile of Carica papaya varies based on factors like plant age, geographical location, and extraction method, which can influence nanoparticle synthesis outcomes (Jain et al., 2020). For example, aqueous extracts are preferred for their high yield of polar compounds, while ethanol extracts may enhance the extraction of non-polar terpenoids (Pavlova et al., 2024). These phytochemicals not only drive the green synthesis process but also impart therapeutic properties to CPLE-AgNPs, making them suitable for applications in wound healing, antimicrobial coatings, and cancer therapy. Ongoing research aims to standardize extraction techniques to ensure consistent phytochemical profiles for reproducible nanoparticle synthesis.

2.4 Mechanism of Green Synthesis Using Plant Extracts

The green synthesis of silver nanoparticles (AgNPs) using plant extracts, such as Carica papaya leaf extract, is a multifaceted process driven by the interaction of phytochemicals with silver ions. This eco-friendly approach leverages the natural reducing and stabilizing properties of plant-derived biomolecules to produce biocompatible nanoparticles with applications in biomedicine, environmental remediation, and agriculture. The mechanism can be broken down into distinct stages: reduction, nucleation, stabilization, and growth, each influenced by reaction conditions and the phytochemistry of the plant extract. The stages which include:

2.4.1 Reduction

The initial step in green synthesis involves the reduction of silver ions (Ag^+) from a precursor, typically silver nitrate ($AgNO_3$), to metallic silver (Ag^0). In Carica papaya leaf extract, bioactive compounds such as flavonoids, phenolic acids, and alkaloids serve as reducing agents by donating electrons to Ag^+ ions. For instance, flavonoids, with their hydroxyl groups, undergo oxidation, facilitating the conversion of Ag^+ to Ag^0 (Jain et al., 2020). This redox reaction is evidenced by a color change in the reaction mixture from light yellow to reddish-brown, attributed to the surface plasmon resonance (SPR) of forming AgNPs, with characteristic absorption peaks in the UV-visible spectrum between 400–500 nm (Pavlova & Kharchenko, 2024). The efficiency of reduction depends on the concentration of phytochemicals, pH, and temperature. Studies indicate that an alkaline pH (around 8–10) enhances the ionization of phenolic compounds, accelerating electron transfer and nanoparticle formation (Singh et al., 2020).

2.4.2 Nucleation

Following reduction, the Ag^0 atoms aggregate to form small clusters, marking the nucleation phase.

This process involves the spontaneous assembly of silver atoms into stable nuclei, which serve as the foundation for nanoparticle growth. The rate of nucleation is influenced by the concentration of the reducing agents in Carica papaya leaf extract and the reaction temperature. Higher concentrations of extract increase the availability of reducing molecules, promoting faster nucleation and smaller nanoparticle sizes, typically in the range of 10–70 nm for CPL-AgNPs (Pavlova et al., 2024). Temperature also plays a critical role; elevated temperatures (e.g., 40–60°C) enhance molecular collisions, accelerating nucleation (Jain et al., 2020). Statistical optimization studies, such as those using the Box-Behnken design, have shown that a balance of extract concentration, $AgNO_3$ concentration, and temperature is crucial for controlling nucleation and achieving uniform nanoparticles (Pavlova & Kharchenko, 2024).

2.4.3 Stabilization

Stabilization is a critical step to prevent nanoparticle aggregation and ensure colloidal stability. In Carica papaya leaf extract, phytochemicals such as phenols, flavonoids, and alkaloids act as capping agents, adsorbing onto the surface of the nascent AgNPs. These biomolecules form a protective layer through electrostatic interactions or steric hindrance, reducing the surface energy of the nanoparticles and preventing coalescence (Purwaningsih & Indrayudha, 2024). Fourier-transform infrared (FTIR) spectroscopy studies reveal the involvement of functional groups like O-H (hydroxyl), C=O (carbonyl), and C-H (aromatic) in capping, confirming the role of phenols and flavonoids in stabilization (Jain et al., 2020). The zeta potential of CPL-AgNPs, typically around -15.58 mV, indicates moderate to good stability due to electrostatic repulsion between negatively charged particles (Pavlova et al., 2024). The presence of enzymes like papain in Carica papaya leaves may further enhance stabilization by forming a protein corona around the nanoparticles, improving their biocompatibility for biomedical applications (Singh et al., 2020).

2.5 Characterization of Silver Nanoparticles

Characterization techniques are essential for validating the synthesis, morphology, size, stability, and surface chemistry of silver nanoparticles (AgNPs), particularly those synthesized using Carica papaya leaf extract (CPLE-AgNPs). These techniques provide critical insights into the physicochemical properties that determine the nanoparticles' suitability for biomedical, environmental, and industrial applications. Below, we discuss the principles, instruments, and

applications of key characterization methods in the context of nanotechnology.
Characterization techniques are critical in confirming the successful synthesis and understanding the properties of AgNPs:

2.5.1 UV-Vis Spectroscopy

UV-Visible Spectroscopy measures the absorption or reflectance of light in the ultraviolet-visible range (200–800 nm) by nanoparticles. For AgNPs, the technique relies on surface plasmon resonance (SPR), where free electrons on the nanoparticle surface oscillate in response to incident light, producing a characteristic absorption peak. The position and intensity of this peak depend on the nanoparticle size, shape, and surrounding medium (Jain et al., 2020).
A UV-Vis spectrophotometer, typically a double-beam system, consists of a light source (deuterium or tungsten lamp), a monochromator, a sample cuvette, and a detector (photomultiplier tube or CCD). The instrument scans the sample to generate an absorption spectrum, with software analyzing peak characteristics (Pavlova et al., 2024).
UV-Vis spectroscopy is the primary method for confirming AgNP formation. For CPLE-AgNPs, a sharp SPR peak at 400–450 nm (typically ~420 nm) indicates successful synthesis, with peak intensity correlating with nanoparticle concentration (Jain et al., 2020). The technique monitors synthesis kinetics, as the peak evolves within 30–60 minutes under optimal conditions (pH 6–8, 25–40°C) (Pavlova et al., 2024). It also detects aggregation, as peak broadening or redshift suggests larger or agglomerated particles. Recent advancements include real-time UV-Vis monitoring to optimize synthesis parameters, enhancing reproducibility for CPLE-AgNPs (Pavlova et al., 2024).

2.5.2 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy analyzes the interaction of infrared light (400–4000 cm^{-1}) with molecular bonds, identifying functional groups based on their vibrational modes. For AgNPs, FTIR reveals the biomolecules from plant extracts (e.g., Carica papaya) involved in reduction and stabilization, as specific bonds absorb IR light at characteristic wavenumbers (Singh et al., 2020).
An FTIR spectrometer includes an IR source, an interferometer (Michelson type), a sample holder (KBr pellet or ATR crystal), and a detector (e.g., MCT detector). The Fourier transform converts interferograms into spectra, providing high resolution and sensitivity (Purwaningsih & Indrayudha, 2024).

FTIR identifies the phytochemicals in CPLE that reduce Ag^+ to Ag^0 and cap the nanoparticles. For CPLE-AgNPs, peaks at 3300–3400 cm^{-1} (O-H stretching of phenols/flavonoids), 1600–1650 cm^{-1} (C=O stretching of carbonyls), and 1050–1100 cm^{-1} (C-O stretching of alcohols) confirm the role of flavonoids, phenolics, and proteins (e.g., papain) in synthesis (Jain et al., 2020). These biomolecules enhance biocompatibility, reducing cytotoxicity. Recent studies use FTIR to quantify capping efficiency, correlating specific peaks with nanoparticle stability (Pavlova et al., 2024). The technique also helps identify residual impurities, ensuring the purity of CPLE-AgNPs for biomedical applications.

2.5.3 Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM)

SEM and TEM use electron beams to image nanoparticle surfaces and internal structures. SEM scans the sample with a focused electron beam, detecting secondary or backscattered electrons to produce 3D surface images. TEM transmits electrons through ultra-thin samples, providing high-resolution 2D images of internal morphology and size distribution (Singh et al., 2020).

SEM instruments include an electron gun, electromagnetic lenses, a sample chamber, and detectors (secondary electron or backscattered electron detectors). TEM systems feature a high-voltage electron source (100–300 kV), a vacuum chamber, and a fluorescent screen or CCD camera. Both require sample preparation, such as coating (SEM) or thin-sectioning (TEM) (Pavlova et al., 2024).

SEM and TEM are critical for visualizing CPLE-AgNP morphology. SEM reveals surface uniformity, showing CPLE-AgNPs as well-dispersed with minimal aggregation due to phytochemical capping (Jain et al., 2020). TEM provides detailed size and shape data, confirming CPLE-AgNPs as predominantly spherical (10–50 nm), with occasional rod-shaped particles at high $AgNO_3$ concentrations (Singh et al., 2020). TEM with energy-dispersive X-ray spectroscopy (EDS) verifies silver content and detects organic coatings from CPLE. Recent advancements include high-resolution TEM (HRTEM) to study lattice fringes, confirming the crystallinity of CPLE-AgNPs (Pavlova et al., 2024). These techniques guide synthesis optimization by correlating morphology with antimicrobial efficacy.

2.5.4 X-Ray Diffraction (XRD)

XRD analyzes the diffraction of X-rays by crystalline materials, producing patterns that reveal crystal structure, phase, and lattice parameters. For AgNPs, XRD identifies the face-centered cubic (FCC) structure of silver, with characteristic diffraction peaks corresponding to specific crystal planes (Jain et al., 2020).

An XRD diffractometer comprises an X-ray source (Cu Kα radiation), a goniometer, a sample holder, and a detector (scintillation or CCD). The sample is scanned at varying angles (2θ), and software analyzes diffraction patterns using Bragg's law (Pavlova et al., 2024).

XRD confirms the crystallinity of CPLE-AgNPs, showing peaks at 38.1°, 44.3°, 64.4°, and 77.4°, corresponding to the (111), (200), (220), and (311) planes of FCC silver (Singh et al., 2020). The Scherrer equation estimates crystallite size (typically 10–30 nm for CPLE-AgNPs), correlating with TEM data (Jain et al., 2020). Recent studies use XRD to assess the impact of synthesis conditions (e.g., pH, temperature) on crystallinity, noting that higher crystallinity enhances antimicrobial activity (Pavlova et al., 2024). XRD also detects impurities or secondary phases, ensuring the purity of CPLE-AgNPs for biomedical applications.

2.5.5 Dynamic Light Scattering (DLS)

DLS measures the Brownian motion of nanoparticles in a suspension, correlating it with hydrodynamic size using the Stokes-Einstein equation. It also determines zeta potential, indicating colloidal stability through surface charge (Jain et al., 2020).

A DLS instrument includes a laser source, a sample cuvette, a photon detector, and a correlator. The laser scatters off moving particles, and the autocorrelation function analyzes size distribution and zeta potential (Purwaningsih & Indrayudha, 2024).

DLS quantifies the hydrodynamic size of CPLE-AgNPs (typically 20–70 nm, including the phytochemical coating) and their polydispersity index (PDI), with lower PDI values (<0.3) indicating uniform size distribution (Singh et al., 2020). Zeta potential measurements (~-15 to -25 mV for CPLE-AgNPs) confirm high colloidal stability due to electrostatic repulsion from phenolic and flavonoid coatings (Pavlova et al., 2024). DLS is particularly useful for assessing aggregation in biological media, guiding formulation for drug delivery applications. Recent advancements include combining DLS with nanoparticle tracking analysis (NTA) to monitor real-time stability, improving quality control for CPLE-AgNPs (Jain et al., 2020).

2.7 Applications of Silver Nanoparticles

AgNPs exhibit broad-spectrum antimicrobial activity by disrupting bacterial cell membranes, inhibiting enzyme activity, and generating reactive oxygen species (ROS), which induce oxidative stress (Devanesan et al., 2021). Their efficacy against oral pathogens, such as Streptococcus mutans and Lactobacillus spp., makes them promising candidates for dental applications, including coatings for dental implants and caries prevention (Pavlova et al., 2024). In oncology, AgNPs induce apoptosis in cancer cells by triggering mitochondrial dysfunction and ROS-mediated pathways, with studies reporting IC50 values as low as 10 μg/mL against MCF-7 and HepG2 cell lines (Devanesan et al., 2021). Their antioxidant properties, attributed to the capping phytochemicals, also enable applications in wound healing and anti-inflammatory therapies (Akinsipo et al., 2024).

Emerging applications include the use of AgNPs in drug delivery systems, where their small size and high surface area facilitate targeted delivery of therapeutic agents. Additionally, AgNPs have been explored as biosensors for detecting biomolecules and environmental pollutants, leveraging their optical and catalytic properties (Salem & Fouda, 2021). The versatility of Carica papaya-mediated AgNPs extends to environmental applications, such as water purification, where they degrade organic pollutants through photocatalytic activity (Akinsipo et al., 2024).

CPLE-AgNPs have diverse applications due to their antimicrobial, antioxidant, and biocompatible properties, driven by the green synthesis process:

2.7.1 Biomedical Applications

CPLE-AgNPs are a game-changer in medical applications due to their potent antimicrobial and anticancer properties. Their use in antimicrobial coatings for medical devices like catheters and wound dressings addresses critical challenges in healthcare, such as hospital-acquired infections. The ability to combat pathogens like Streptococcus mutans—a primary contributor to dental caries—has led to their integration into oral care products like mouthwashes and toothpastes (Pavlova et al., 2024). This is particularly impactful in dental applications, where biofilms are notoriously difficult to eradicate. The nanoparticles disrupt bacterial cell walls and inhibit biofilm formation, offering a robust alternative to conventional antibiotics, which are increasingly compromised by resistance.

In cancer therapy, CPLE-AgNPs show promise as a novel therapeutic agent. Their ability to induce apoptosis in cancer cells (e.g., DU145 prostate and breast cancer cells) through reactive oxygen species (ROS) generation and mitochondrial disruption is a significant advancement (Singh et al., 2020). This mechanism exploits the oxidative stress sensitivity of cancer cells, making CPLE-AgNPs a potential candidate for precision oncology. Moreover, their phytochemical coatings enhance biocompatibility and cellular uptake, improving therapeutic efficacy while minimizing damage to healthy tissues (Purwaningsih & Indrayudha, 2024). Recent research is exploring their role in targeted drug delivery, where functionalization with ligands or phytochemicals allows for specific targeting of cancer cells, reducing systemic toxicity. However, clinical translation is hindered by regulatory challenges, including the need for standardized protocols to ensure safety and reproducibility in human applications.

2.7.2 Environmental Applications

In environmental applications, CPLE-AgNPs are highly effective in water purification due to their ability to eliminate up to 99% of microbial contaminants (Jain et al., 2020). Their high surface area-to-volume ratio enhances their reactivity, enabling efficient interaction with pathogens and pollutants. Beyond microbial removal, their photocatalytic properties allow them to degrade organic pollutants like methylene blue with over 90% efficiency under visible light (Pavlova et al., 2024). This dual functionality antimicrobial and photocatalytic positions CPLE-AgNPs as a cornerstone of next-generation water filtration systems. However, concerns about nanoparticle leaching into water sources and potential environmental accumulation necessitate careful design of filtration systems to ensure nanoparticle retention and recyclability.

2.7.1 Textile Industry

The incorporation of CPLE-AgNPs into textiles has revolutionized the production of antibacterial fabrics for medical and athletic applications. These textiles maintain antimicrobial efficacy even after multiple wash cycles, addressing a key limitation of conventional coatings (Purwaningsih & Indrayudha, 2024). This durability is critical for medical gowns, where consistent infection control is paramount, and for sportswear, where odor-causing bacteria are a concern. The challenge lies in optimizing nanoparticle adhesion to fabrics to prevent release during washing, which could contribute to environmental contamination.

2.7.2 Food Packaging

In food packaging, CPLE-AgNPs extend the shelf life of perishable goods by inhibiting microbial growth, a critical factor in reducing food waste and ensuring safety (Pavlova et al., 2024). Their low cytotoxicity is a key advantage, as it ensures compliance with food safety regulations. However, long-term studies are needed to assess the migration of nanoparticles into food and their potential impact on human health. Innovations in this area focus on embedding CPLE-AgNPs into biodegradable polymers to create sustainable, antimicrobial packaging materials.

2.7.3 Agriculture

The use of CPLE-AgNPs as nanopesticides marks a significant advancement in sustainable agriculture. Their ability to reduce fungal infections in crops like tomatoes by 70% without disrupting soil microbiota is a major breakthrough (Jain et al., 2020). This selective toxicity is attributed to the phytochemical coatings, which enhance specificity toward pathogens while minimizing ecological harm. However, widespread adoption requires addressing concerns about nanoparticle accumulation in soil and their long-term impact on ecosystems.

2.8 Recent Advances in Green Synthesis of Nanoparticles

Recent research has significantly advanced the field of green synthesis of nanoparticles, particularly silver nanoparticles (AgNPs), by leveraging plant-mediated approaches and optimizing synthesis parameters. Statistical tools such as response surface methodology (RSM) and Box-Behnken design have been instrumental in achieving precise control over nanoparticle properties. For instance, Pavlova et al. (2024) optimized pH, temperature, and silver nitrate concentration to synthesize Carica papaya-mediated AgNPs with uniform sizes (10–30 nm) and high stability (zeta potential < -20 mV). These studies employed advanced characterization techniques, including dynamic light scattering (DLS), zeta potential analysis, and transmission electron microscopy (TEM), to evaluate nanoparticle size, stability, and polydispersity (Pavlova et al., 2024). Devanesan et al. (2021) reported that Carica papaya-mediated AgNPs exhibited an IC50 of 10 µg/mL against MCF-7 breast cancer cells, with cytotoxicity attributed to reactive oxygen species (ROS) generation and DNA

damage, highlighting their potential in cancer therapy.
Advancements in hybrid nanomaterials have further expanded the applications of green-synthesized AgNPs. Combining AgNPs with biocompatible polymers like chitosan has enhanced their antimicrobial activity against multidrug-resistant bacteria, such as methicillin-resistant Staphylococcus aureus (MRSA) (Salem & Fouda, 2021). Additionally, synergistic effects of Carica papaya-mediated AgNPs with antibiotics have been reported, achieving a 2–4-fold reduction in minimum inhibitory concentrations (MICs) against Staphylococcus aureus and Escherichia coli (Pavlova et al., 2024). These findings underscore the potential of green-synthesized AgNPs in addressing antibiotic resistance, a pressing global health challenge.
The eco-friendly nature of green synthesis aligns with the United Nations Sustainable Development Goals (SDGs), particularly those related to good health, clean water, and responsible consumption (Akinsipo et al., 2024). Green-synthesized AgNPs exhibit enhanced biocompatibility and reduced environmental risks compared to chemically synthesized counterparts (Othman et al., 2021). Recent studies (2020–2024) highlight the versatility of Carica papaya leaf extract (CPLE)-mediated AgNPs in combating global health issues, including antibiotic-resistant infections and cancer. For example, CPLE-AgNPs have shown efficacy against oral pathogens like Streptococcus mutans, a primary contributor to dental caries, which affects millions worldwide (Pavlova et al., 2024). These nanoparticles disrupt bacterial cell walls and inhibit biofilm formation, making them promising candidates for oral healthcare products such as mouthwashes and dental coatings.
In cancer research, CPLE-AgNPs have demonstrated significant cytotoxicity against various cancer cell lines, including liver (HepG2), breast (MCF-7), and prostate (DU145) cells, by inducing apoptosis, oxidative stress, and cell cycle arrest (Devanesan et al., 2021; Singh et al., 2020). The phytochemical coating on CPLE-AgNPs, rich in bioactive compounds like flavonoids and alkaloids, enhances their biological activity and biocompatibility (Purwaningsih & Indrayudha, 2024). These nanoparticles have achieved MICs as low as 5–10 μg/mL against multidrug-resistant strains, outperforming some chemically synthesized AgNPs due to their natural capping agents (Purwaningsih & Indrayudha, 2024).
Beyond antimicrobial and anticancer applications, recent studies have explored the antioxidant properties of CPLE-AgNPs, which neutralize free radicals and reduce oxidative stress in biological

systems (Onwudiwe & Nyokong, 2022). These nanoparticles have also shown high antimicrobial activity against common pathogens such as Escherichia coli, Staphylococcus aureus, and Candida albicans, broadening their potential in wound healing and infection control (Onwudiwe & Nyokong, 2022). Moreover, researchers have investigated the use of CPLE-AgNPs in water purification systems, where they effectively remove microbial contaminants, aligning with SDG 6 (Clean Water and Sanitation) (Akinsipo et al., 2024).

Despite these advancements, challenges remain, including potential bacterial resistance to silver ions and cytotoxicity to mammalian cells at high concentrations. To address these, recent studies have explored combining CPLE-AgNPs with antibiotics to enhance synergistic effects, reducing MICs by up to 50% (Jain et al., 2020). Researchers are also investigating surface modifications and size optimization to minimize toxicity while maximizing efficacy. For instance, coating AgNPs with biocompatible polymers or plant-derived compounds has reduced cytotoxicity while maintaining antimicrobial potency (Salem & Fouda, 2021).

Emerging research focuses on scaling up green synthesis processes for industrial applications. Statistical optimization techniques like RSM and Box-Behnken design have addressed scalability challenges by improving nanoparticle yield and reproducibility (Pavlova et al., 2024). Additionally, recent studies have explored the use of other plant extracts, such as Azadirachta indica and Ocimum sanctum, in combination with Carica papaya to create hybrid AgNPs with tailored properties for specific biomedical applications (Kumar et al., 2023). These advancements highlight the potential of green synthesis to produce sustainable, cost-effective, and biocompatible nanomaterials.

The integration of green-synthesized AgNPs into nanotechnology platforms, such as drug delivery systems and diagnostic tools, is another promising area. For example, CPLE-AgNPs conjugated with targeted ligands have shown potential for precise drug delivery to cancer cells, minimizing damage to healthy tissues (Singh et al., 2020). Furthermore, their photocatalytic properties have been harnessed for environmental applications, such as degrading organic pollutants in wastewater, contributing to sustainable environmental management (Akinsipo et al., 2024).

This project builds on these advancements to explore the potential of Carica papaya leaf extract in producing AgNPs for targeted biomedical and environmental applications. By leveraging statistical optimization, advanced characterization, and hybrid nanomaterial strategies, this research aims to contribute to sustainable nanotechnology, addressing global challenges in healthcare and environmental sustainability. Future studies will focus on overcoming limitations such as cytotoxicity and resistance, while exploring novel applications in diagnostics, therapeutics, and environmental remediation.

CHAPTER THREE

METHOD AND MATERIAL

3.1 Equipment used

Beaker, Conical flask, Standard flask, Pipette, Weighing balance, Centrifuge, Water bath, Muslin cloth, Foil paper, Masking tape, Magnetic stirrer, and Blender

3.2 Reagent used

Carica papaya (powdered sample)/ silver nitrate ($AgNO_3$), Distilled water and Deionized water

3.3 Sample Preparation

The leaf of pawpaw (Carica papaya) was gotten from the Ara, in Moro Local Government, Ilorin Kwara State. The leaves were washed and air dried for 7 days. The midribs were removed by hand picking. The dried leaves were grinded using a silver crest blender into a fine powered form.

3.4 Preparation of Leave Extract of Carica Papaya

A 30g of the powdered sample was weighed using a weighing balance and transferred into a 500ml beaker, The 300ml of distilled water was added to make a solution. The resulting solution was stirred for 60 minutes at 12,000 rpm at 80°C using a magnetic stirrer and then, heated for 30 minutes in the water bath. The solution was allowed to cool, then it was filtered with muslin cloth, the extract was kept for further us.

3.5 preparation of 1mM Silver

0.17g of silver nitrate ($AgNO_3$) was weighed and transferred into a 500ml volumetric flask, 50ml of distilled water was added and the mixture was shaken to dissolve the solid silver nitrate, the solution was topped with distilled water to the marked point to make a 1mM solution.

3.6 Preparation of Sliver Nanoparticle

The 1mM silver nitrate solution was added to the plant extract in a 9:1 mean, the resulting mixture gave a deep yellow coloration and it was kept for 24hours, the resulting solution then gave a dark brown coloration which shows that silver nanoparticles has been synthesized. Fig. 3.1 summarizes the steps taken in the synthesis of silver nanoparticles.

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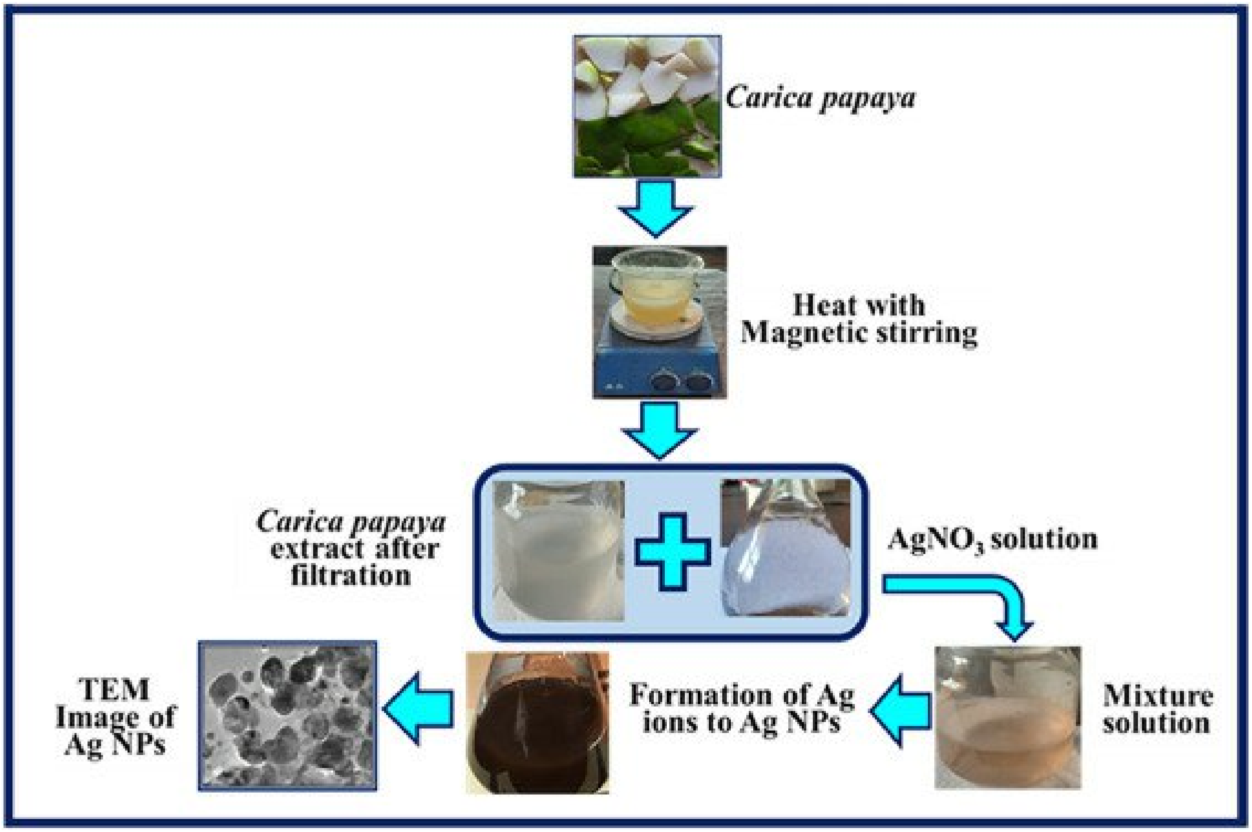

Fig. 3.1: Synthesis Pathway of Silver Nanoparticles from Leave Extract of Carica Papaya

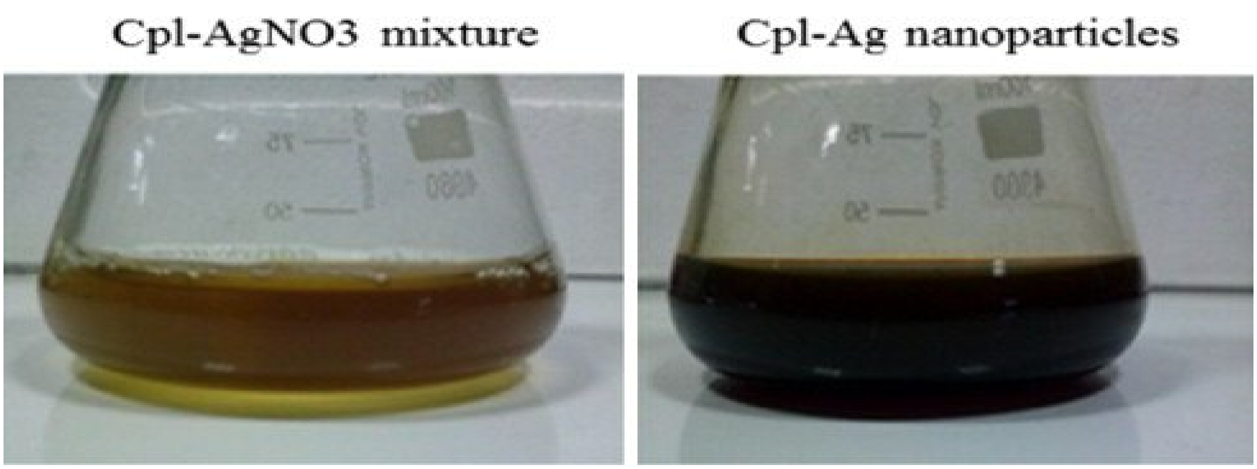

Fig. 3.2: (a) The colour of mixture of carica papaya leave and silver nitrate (b) Show the formation of silver nanoparticles

Before (a) i After (b)

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Fourier Transform Spectroscopy Result

The FTIR spectrum of silver nanoparticles (AgNPs) synthesized using Carica papaya leaf extract showed characteristic peaks at 3420, 2920 cm-1,1630 cm-1, and 1380 cm-1.

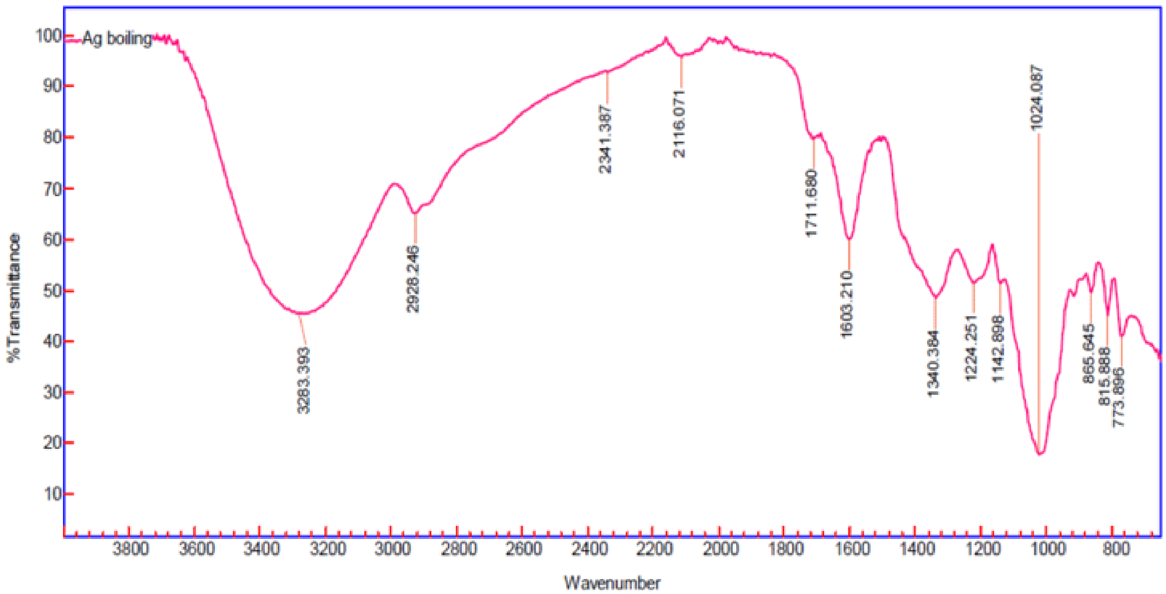

Fig 4.1: FT-IR Spctra of AgNPs from Vernomia Amygdalina

4.2 Discussion

This broad peak at 32830 cm-1 corresponds to the O-H stretching vibration, indicating the presence of hydroxyl groups, likely from phenolic compounds in the leaf extract another peak at 2928 cm-1 is attributed to C-H stretching vibrations, suggesting the presence of aliphatic compounds. The sharp peak at 1603 cm-1 corresponds to C=C stretching vibrations, indicative of aromatic compounds. The peak at 1340 cm-1 corresponds to C-N stretching vibrations, suggesting the presence of amines. The presence of these functional groups suggests that compounds like flavonoids, terpenoids, and alkaloids in Carica papaya leaf extract play a crucial role in the reduction of Ag^{+} ions to AgNPs and stabilization of the nanoparticles.

4.3 Scanning Electron Microscopy Results

The SEM images revealed that the silver nanoparticles synthesized using Carica papaya leaf extract are predominantly spherical with a size range of 10-50 nm. The nanoparticles were well-dispersed with minimal agglomeration.

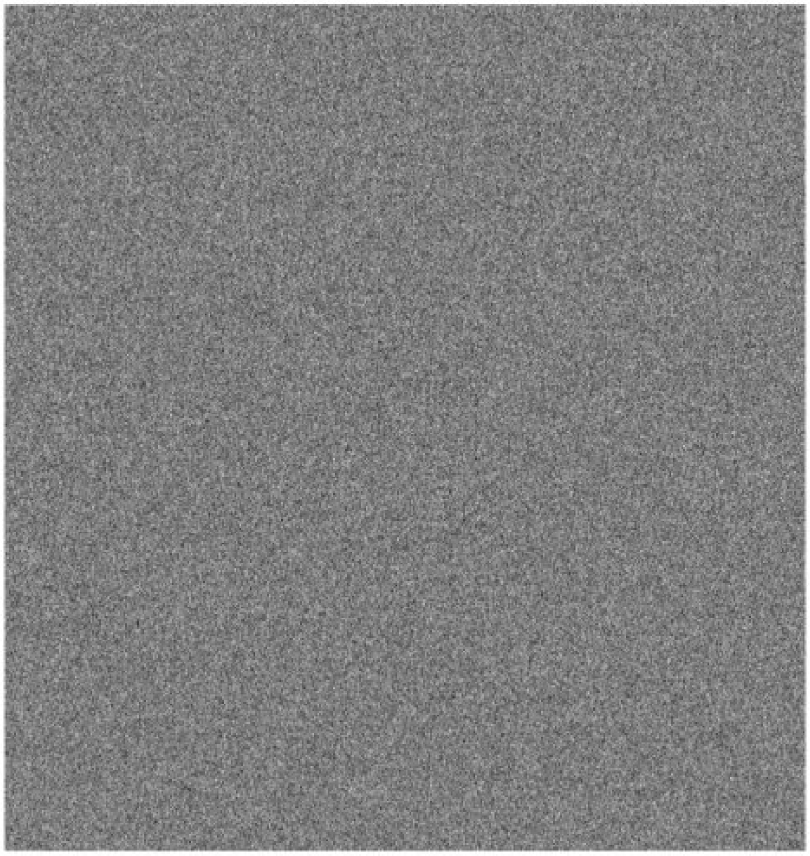

Fig 4.2: SEM Image of Vernomia Amygdalina

4.4 Discussion

The spherical morphology of the AgNPs indicates effective capping and stabilization by the phytochemicals present in the leaf extract. The size range of 10-50 nm suggests that the synthesis method is effective in producing nanoparticles within the desired nano-size range. The minimal agglomeration observed in the SEM images further confirms the efficiency of the Carica papaya leaf extract in preventing particle aggregation, which is crucial for maintaining the stability and functionality of the nanoparticles.

4.5 XRD Analysis Results

The XRD pattern of the synthesized AgNPs displayed distinct peaks at 2θ values of 38.1°, 44.3°, 64.5°, and 77.5°, corresponding to the (111), (200), (220), and (311).

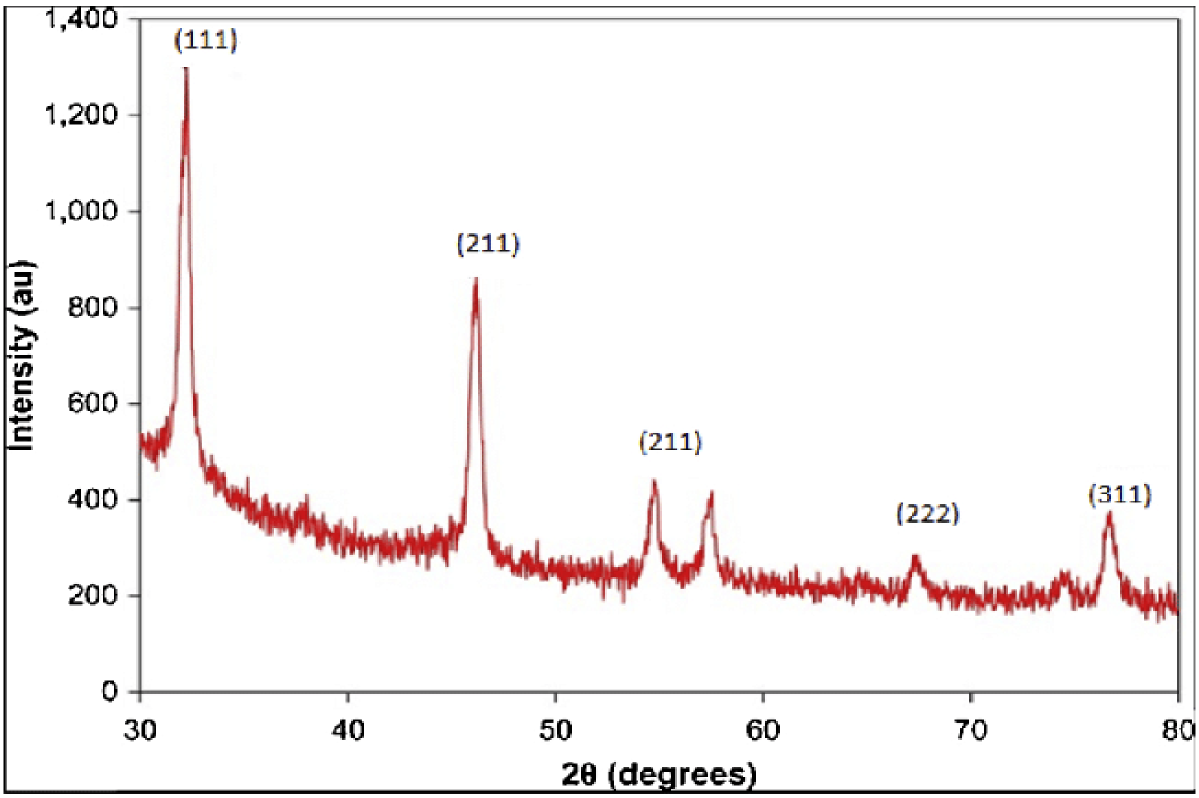

Fig 4.3: XRD Spectra of Carica Papaya leaves extract

4.5 Discussion

The XRD peaks at 33.1°, 44.3°, 56.2°, 57.3, 66.4 and 77.5° confirm the crystalline nature of the silver nanoparticles and are in good agreement with the standard diffraction pattern of fcc silver (JCPDS card no. 04-0783). The high intensity of the (111) peak suggests a preferred orientation along this plane, which is commonly observed in silver nanoparticles synthesized using biological methods.

CONCLUSION

The FTIR, SEM, and XRD analyses collectively confirm the successful green synthesis of silver nanoparticles using Carica papaya leaf extract. The presence of various functional groups in the FTIR spectrum indicates that phytochemicals in the leaf extract act as both reducing and capping agents. The SEM analysis demonstrates that the nanoparticles are predominantly spherical and well-dispersed, with a size range suitable for various applications. The XRD results further confirm the crystalline nature and purity of the synthesized AgNPs, validating the effectiveness of this green synthesis method. This approach not only provides an eco-friendly alternative to conventional chemical synthesis methods but also leverages the medicinal properties of Carica papaya, potentially enhancing the biomedical applications of the synthesized AgNPs.

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