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Green Synthesis of Silver Nanoparticles Using Moringa oleifera leaf Extract

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Abstract : *The present study focuses on the green synthesis of silver nanoparticles (AgNPs) using Moringa oleifera leaf extract as a natural reducing and stabilizing agent. Nanotechnology has emerged as a rapidly advancing field due to the unique physicochemical properties of nanoparticles and their wide range of applications in medicine, biotechnology, environmental science, and industry. Among various metallic nanoparticles, silver nanoparticles have gained significant attention because of their excellent antimicrobial, catalytic, antioxidant, and biomedical properties. Conventional methods for nanoparticle synthesis often involve toxic chemicals, high energy consumption, and environmental concerns. Therefore, green synthesis has been developed as an eco-friendly and sustainable alternative. Moringa oleifera was selected for this study because its leaves contain abundant phytochemicals such as flavonoids, phenolic compounds, tannins, proteins, and antioxidants that facilitate the reduction of silver ions (Ag^+) into silver nanoparticles (AgNPs). The synthesis process was carried out by reacting aqueous Moringa oleifera leaf extract with silver nitrate ($AgNO_3$) solution, resulting in the formation of silver nanoparticles. The synthesized nanoparticles were characterized using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD) techniques to determine their morphology, size, and crystalline nature. The study also highlights the potential applications of silver nanoparticles in antimicrobial treatments, water purification, pollution control, and environmental remediation. The findings suggest that green synthesis using Moringa oleifera leaf extract is a simple, cost-effective, and environmentally friendly method for producing silver nanoparticles. The synthesized nanoparticles possess desirable physicochemical characteristics and offer significant potential for biomedical, environmental, agricultural, and industrial applications. Thus, plant-mediated synthesis represents a sustainable approach for the development of advanced nanomaterials and supports the growing demand for green nanotechnology.*

Key Words: Silver nanoparticles, Moringa oleifera leaf Extract, green synthesis

I. INTRODUCTION

Nanotechnology is one of the fastest-growing and most innovative fields of modern science, involving the design, synthesis, characterization, and application of materials at the nanoscale level, typically ranging from 1 to 100 nano meters (nm). Materials at this scale exhibit unique physical, chemical, optical, electrical, and biological properties that differ significantly from those of their bulk counterparts due to their high surface-area-to-volume ratio and quantum confinement effects. According to Ahmed et al. (2016), nanoparticles have gained tremendous importance because their size-dependent properties enable novel applications in medicine, biotechnology, electronics, environmental remediation, food preservation, cosmetics, catalysis, and energy-related technologies. The rapid advancement of nanotechnology has opened new opportunities for the development of advanced functional materials with enhanced performance and improved efficiency. Nanoparticles possess unique characteristics such as high reactivity, enhanced catalytic activity, superior mechanical strength, and excellent optical properties. Iravani (2011) reported that nanotechnology has become increasingly important in several scientific and industrial sectors, including biomedical sciences, chemical industries, optoelectronics, drug delivery systems, sensors, and environmental engineering. The

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ability to control particle size and shape at the nanoscale enables the development of materials with tailored properties for specific applications. As a result, nanoparticles have become valuable tools in medical imaging, biosensing, cancer therapy, tissue engineering, and antimicrobial treatments.

Among the various types of nanoparticles, metallic nanoparticles have attracted considerable attention due to their exceptional physicochemical and biological properties. Silver, gold, platinum, copper, and zinc nanoparticles are among the most extensively studied metallic nanomaterials. Among them, silver nanoparticles (AgNPs) are considered one of the most important and widely used nanomaterials because of their remarkable antimicrobial, antiviral, antifungal, anti-inflammatory, catalytic, and optical properties (Ahmed et al., 2016). Silver nanoparticles exhibit excellent chemical stability, high electrical conductivity, and strong biological activity, making them suitable for numerous applications in medicine, pharmaceuticals, food packaging, textiles, cosmetics, water treatment, and electronic industries.

One of the most significant properties of silver nanoparticles is their broadspectrum antimicrobial activity. Silver nanoparticles have demonstrated effective inhibition against a wide range of pathogenic microorganisms, including Grampositive and Gram-negative bacteria. According to Iravani (2011), silver nanoparticles exert their antimicrobial effects by interacting with microbial cell membranes, generating reactive oxygen species (ROS), disrupting cellular metabolism, and interfering with DNA replication processes. These mechanisms lead to cell damage and eventual microbial death. Due to the increasing prevalence of antibiotic-resistant bacterial strains, silver nanoparticles have emerged as promising alternatives and complementary agents to conventional antibiotics.

Silver nanoparticles can be synthesized using physical, chemical, and biological approaches. Physical methods such as evaporation-condensation, laser ablation, and thermal decomposition are capable of producing nanoparticles with controlled morphology and size. Chemical methods commonly involve reducing agents such as sodium borohydride, sodium citrate, and hydrazine for the reduction of silver ions into nanoparticles. However, these conventional methods often require expensive instrumentation, high energy consumption, and toxic chemicals, which may generate hazardous by-products and pose environmental and health risks (Ahmed et al., 2016). Therefore, the development of environmentally friendly and sustainable synthesis methods has become an important area of research in nanotechnology

Green synthesis has emerged as an eco-friendly alternative to traditional nanoparticle synthesis methods. This approach utilizes biological resources such as plant extracts, microorganisms, enzymes, biodegradable polymers, and natural biomolecules as reducing and stabilizing agents. Mittal et al. (2013) emphasized that green synthesis offers several advantages, including low toxicity, cost-effectiveness, simplicity, environmental compatibility, and suitability for largescale production. Unlike conventional chemical methods, green synthesis minimizes the use of hazardous substances and follows the principles of green chemistry. Consequently, it has gained significant attention as a sustainable strategy for nanoparticle production.

Among the various green synthesis approaches, plant-mediated synthesis has become particularly attractive due to its simplicity, efficiency, and economic feasibility. Plant extracts contain a wide range of phytochemicals, including flavonoids, polyphenols, terpenoids, alkaloids, proteins, carbohydrates, and phenolic compounds, which act as natural reducing and capping agents during nanoparticle synthesis. These bioactive compounds facilitate the conversion of metal ions into nanoparticles while simultaneously stabilizing the synthesized particles and preventing their aggregation (Mittal et al., 2013). Furthermore, plantbased synthesis eliminates the need for maintaining microbial cultures and sterile laboratory conditions, making it more practical and scalable for industrial applications. Moringa oleifera, commonly known as the drumstick tree or miracle tree, is one of the most widely studied medicinal plants used in green nanotechnology. The plant is highly valued for its nutritional and therapeutic properties and has been extensively utilized in traditional medicine. According to Anwar et al. (2007), Moringa oleifera contains numerous bioactive compounds such as flavonoids, polyphenols, vitamins, amino acids, proteins, and phenolic acids. These phytochemicals possess strong antioxidant and reducing properties that make the plant highly suitable for nanoparticle synthesis. In

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addition, Moringa oleifera exhibits antimicrobial, anti-inflammatory, antidiabetic, antioxidant, and anticancer activities, which further enhance its biomedical significance.

The phytochemical constituents present in Moringa oleifera leaf extract play a vital role in the reduction of silver ions (Ag^+) into silver nanoparticles and their subsequent stabilization. The use of Moringa oleifera leaf extract provides an environmentally friendly and sustainable approach for synthesizing biologically active silver nanoparticles without the need for toxic chemicals. Therefore, the present study focuses on the green synthesis of silver nanoparticles using Moringa oleifera leaf extract as a natural reducing and stabilizing agent. The synthesized nanoparticles are expected to possess desirable physicochemical characteristics and significant antibacterial activity, making them suitable for various biomedical, environmental, and industrial applications.

Moringa oleifera, commonly known as the drumstick tree or miracle tree, belongs to the family Moringaceae and is widely cultivated in tropical and subtropical regions. It is considered one of the most important medicinal and nutritional plants due to its rich phytochemical composition and diverse therapeutic applications. According to Anwar et al. (2007), almost every part of the plant, including leaves, seeds, flowers, roots, bark, and pods, possesses significant medicinal value and has been traditionally used for the treatment of various diseases. The leaves of Moringa oleifera are particularly rich in bioactive compounds such as flavonoids, phenolic compounds, tannins, saponins, proteins, vitamins, essential amino acids, calcium, iron, and antioxidant molecules (Anwar et al., 2007). These phytochemicals are responsible for the plant's strong antioxidant and therapeutic properties. The high concentration of natural antioxidants helps protect cells from oxidative stress and contributes to the prevention of various chronic diseases (Anwar et al., 2007).

In traditional medicine, Moringa oleifera has been extensively used for the treatment of diabetes, asthma, hypertension, liver disorders, inflammatory diseases, microbial infections, and digestive problems (Anwar et al., 2007). Several studies have reported that the plant exhibits antibacterial, anti-inflammatory, antidiabetic, anticancer, and hepatoprotective activities due to the presence of biologically active phytochemicals (Anwar et al., 2007). Furthermore, compounds such as flavonoids, phenolic acids, niazimicin, and β-sitosterol present in the leaves contribute significantly to its pharmacological potential (Anwar et al., 2007). The nutritional value of Moringa oleifera is equally important. The leaves contain substantial amounts of proteins, vitamins, minerals, and essential amino acids, making them valuable as dietary supplements and functional food ingredients (Anwar et al., 2007). Because of its exceptional nutritional profile, Moringa oleifera has been widely recognized as a natural source of health-promoting compounds

In recent years, Moringa oleifera has gained considerable attention in the field of green nanotechnology. The phytochemicals present in the leaf extract act as natural Page | 7 reducing and stabilizing agents during the synthesis of metal nanoparticles. These compounds facilitate the conversion of metal ions into nanoparticles while simultaneously preventing particle aggregation and improving nanoparticle stability (Prasad et al., 2011). Due to this property, Moringa oleifera leaf extract has become an effective biological material for the eco-friendly synthesis of silver nanoparticles. Thus, the rich phytochemical composition, medicinal importance, nutritional value, and reducing capability of Moringa oleifera make it a highly valuable plant for biomedical, pharmaceutical, environmental, and nanotechnological applications (Anwar et al., 2007; Prasad et al., 2011).

Moringa oleifera is a well-known medicinal plant valued for its nutritional and health benefits. (Anwar et al., 2007). Recent studies have shown that Moringa oleifera leaf extract can also act as an effective reducing agent in chemical reactions, especially in the field of nanotechnology and green chemistry. The leaf extract contains many bioactive compounds such as flavonoids, polyphenols, terpenoids, and phenolic compounds, which help in reducing metal ions. (Dauthal & Mukhopadhyay, 2016). Moringa oleifera leaf extract shows strong reducing ability when used in the synthesis of metal nanoparticles. It helps convert metal ions into nanoparticles while also improving their stability. Because of this, Moringa oleifera plays an important role in environmentally friendly nanoparticle synthesis. (Prasad et al., 2011; Hemlata et al., 2020).

Nanotechnology has emerged as a rapidly developing field of science and technology, offering innovative solutions in medicine, biotechnology, agriculture, environmental science, and material engineering. Nanoparticles exhibit unique

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physicochemical properties, including enhanced optical, catalytic, electrical, and biological characteristics, due to their nanoscale dimensions and high surface-areato-volume ratio. Among various nanomaterials, silver nanoparticles (AgNPs) have gained considerable attention because of their excellent antimicrobial, antioxidant, anti-inflammatory, and catalytic properties. According to Ahmed et al. (2016), silver nanoparticles have become one of the most extensively studied nanomaterials owing to their broad range of industrial and biomedical applications.

Conventional methods for synthesizing silver nanoparticles include physical and chemical approaches. Physical methods often require sophisticated instruments, high energy consumption, and controlled operating conditions, whereas chemical methods involve toxic reducing and stabilizing agents that may generate hazardous by-products. To overcome these limitations, environmentally friendly synthesis techniques have been developed. Iravani (2011) reported that biological synthesis methods using plants, microorganisms, and natural biomolecules provide sustainable alternatives to conventional nanoparticle production. These methods are eco-friendly, cost-effective, and capable of producing stable nanoparticles under mild reaction conditions. Plant-mediated synthesis has emerged as one of the most promising green approaches for nanoparticle production. According to Mittal et al. (2013), plant extracts contain various phytochemicals such as flavonoids, phenolic compounds, terpenoids, alkaloids, proteins, and carbohydrates that act as natural reducing and capping agents during nanoparticle synthesis. These compounds facilitate the conversion of metal ions into nanoparticles and simultaneously stabilize the synthesized particles, eliminating the need for additional chemical reagents. Furthermore, plant-based synthesis is simple, rapid, economical, and suitable for large-scale production.

The importance of biological resources in nanoparticle synthesis has been extensively discussed by Singh et al. (2016). The authors highlighted that both plants and microorganisms can successfully synthesize metallic nanoparticles with controlled size and morphology. Biological synthesis methods are considered Page | 10 advantageous because they reduce environmental pollution and improve the biocompatibility of nanoparticles. The study also emphasized that reaction conditions such as pH, temperature, extract concentration, and reaction time significantly influence nanoparticle characteristics.

Similarly, Srikar et al. (2016) reviewed the potential of plant-mediated synthesis for producing silver nanoparticles and reported that biosynthesized nanoparticles exhibit significant antimicrobial activity against various pathogenic microorganisms. The authors further noted that green-synthesized silver nanoparticles have applications in drug delivery systems, wound healing, biosensors, diagnostics, and environmental remediation. Their findings highlighted the growing importance of green nanotechnology in modern biomedical research. Recent developments in green nanoparticle synthesis have been summarized by Jadoun et al. (2021), who emphasized the critical role of phytochemicals in the reduction and stabilization of nanoparticles. The review demonstrated that medicinal plants are increasingly being utilized for nanoparticle synthesis due to their rich bioactive composition and strong reducing capability. The authors also reported that plant-mediated synthesis offers better sustainability and lower toxicity compared to conventional methods.

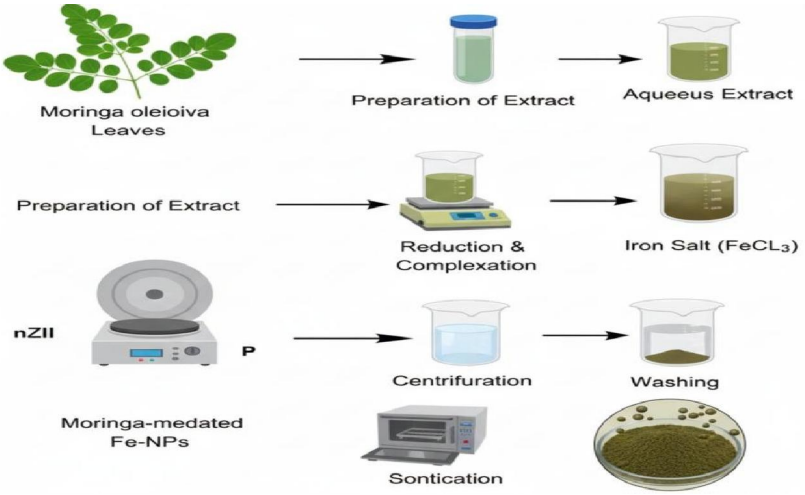
Further advancements in biosynthesized nanoparticles were reviewed by Saratale et al. (2023). Their study highlighted the role of plant-derived metabolites such as polyphenols, flavonoids, proteins, and reducing sugars in nanoparticle formation. The authors reported that biosynthesized nanoparticles have shown promising applications in healthcare, wastewater treatment, agriculture, food technology, and environmental protection. The review also emphasized the growing global interest in developing green nanomaterials for sustainable technological applications. According to Ameen et al. (2021), green synthesis has become a preferred approach for nanoparticle production because it combines environmental sustainability with enhanced biological performance. The authors concluded that plant-mediated nanoparticles exhibit improved biocompatibility, reduced toxicity, and excellent antimicrobial activity, making them highly suitable for biomedical and pharmaceutical applications. Overall, the literature indicates that green synthesis using plant extracts is an effective, eco-friendly, and sustainable method for producing silver nanoparticles. Previous studies have demonstrated that biologically synthesized nanoparticles possess desirable physicochemical properties and significant biological activities.

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II. METHODOLOGY

The green synthesis of silver nanoparticles (AgNPs) was carried out using Moringa oleifera leaf extract following the methods reported by Hemlata et al. (2020), Reddy et al. (2014), Song and Kim (2009), and Dauthal and Mukhopadhyay (2016).

Collection and Preparation of Plant Material Fresh Moringa oleifera leaves were collected and thoroughly washed with tap water followed by distilled water to remove dust and other impurities. The cleaned leaves were shade-dried and used for the preparation of aqueous leaf extract (Hemlata et al., 2020).



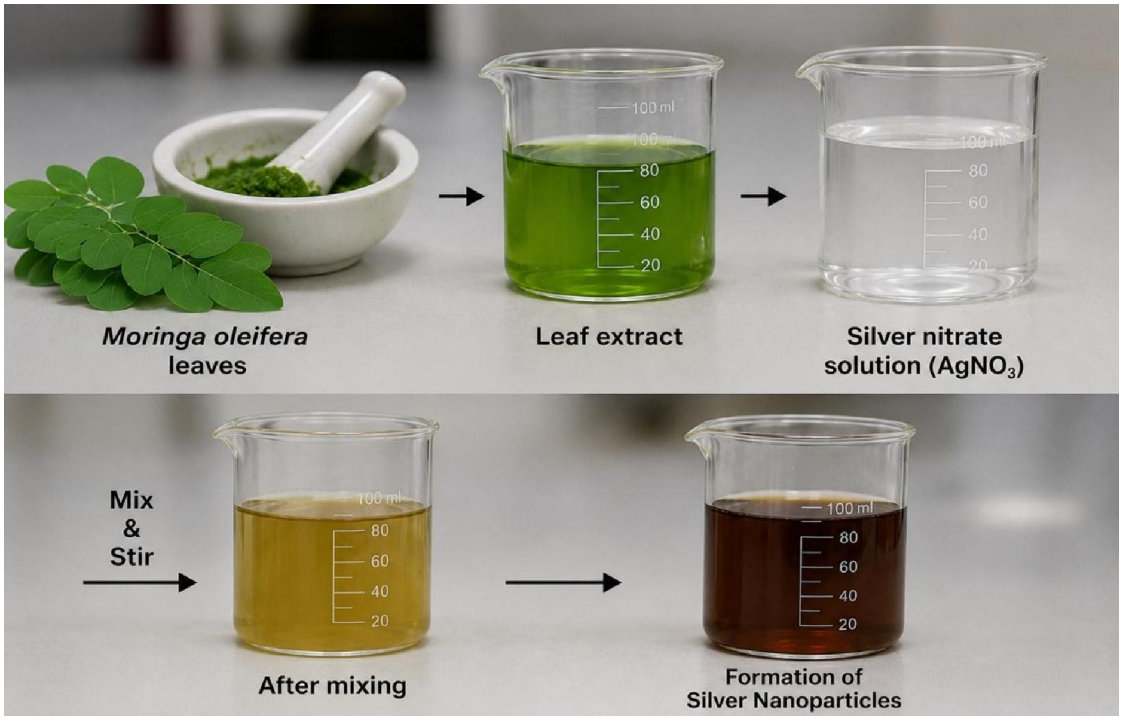
2. Preparation of Leaf Extract Approximately 10 g of fresh leaves were cut into small pieces and boiled in 100 mL of distilled water for 10–15 minutes. The mixture was allowed to cool and then filtered through Whatman No.1 filter paper to obtain a clear extract. The filtrate was stored at 4°C for further experimental use (Reddy et al., 2014).

3. Preparation of Silver Nitrate Solution A 1 mM aqueous silver nitrate ($AgNO_3$) solution was prepared using distilled water. The solution was stored in a dark container to prevent light-induced decomposition (Song & Kim, 2009). 4. Synthesis of Silver Nanopartics

4. Synthesis of Silver Nanoparticles The prepared Moringa oleifera leaf extract was added dropwise to the silver nitrate solution under continuous stirring at room temperature. The reaction mixture was observed for a color change from pale yellow to dark brown, indicating the reduction of silver ions (Ag^+) to silver nanoparticles (AgNPs). The reaction was allowed to proceed for complete nanoparticle formation (Dauthal & Mukhopadhyay, 2016; Hemlata et al., 2020).

5. Purification of Silver Nanoparticles The synthesized nanoparticles were separated by centrifugation at high speed. The collected pellet was washed several times with distilled water and ethanol to remove unreacted materials and impurities. The purified nanoparticles were dried and stored for further characterization (Reddy et al., 2014)

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III. CHARACTERIZATION TECHNIQUES

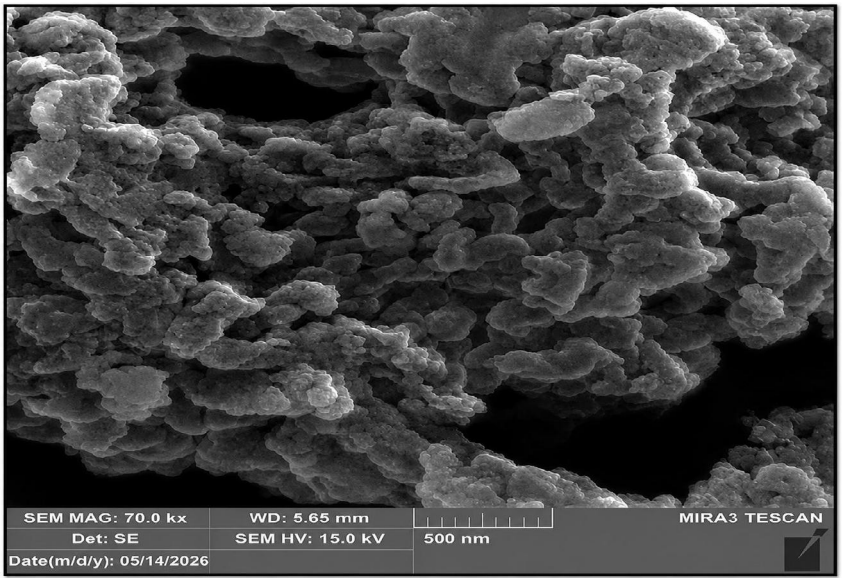
Characterization of nanoparticles is a crucial step in understanding their size, shape, structure, and potential applications. In green synthesis, especially when plant extracts such as Moringa oleifera are used, characterization techniques help confirm the formation of nanoparticles and evaluate their properties. This section focuses on the key characterization techniques used to analyse nanoparticles synthesized through green synthesis methods. By using a combination of optical and structural analysis tools, valuable information about the nanoparticles can be obtained. These techniques support their application in medicine, catalysis, and environmental remediation. The commonly used characterization techniques in the green synthesis of nanoparticles are Scanning Electron Microscopy (SEM) ,Transmission Electron Microscopy (TEM) and X-ray Diffraction (XRD)

IV. RESULTS AND DISCUSSION

SEM Analysis :-

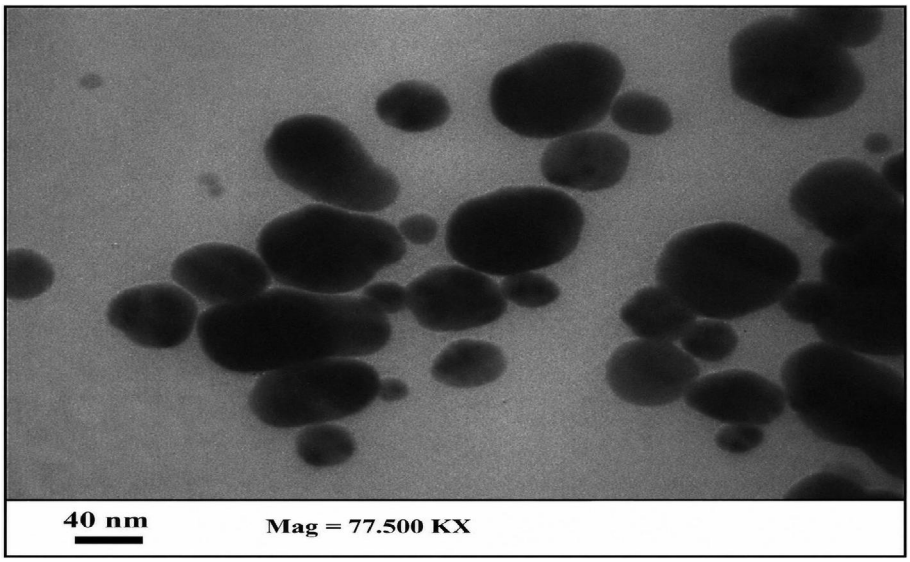
Scanning Electron Microscopy (SEM) was used to study the surface morphology of the synthesized silver nanoparticles. The SEM image revealed irregularly shaped and aggregated nanoparticles with a rough surface structure. The particles formed clustered networks, indicating successful nanoparticle synthesis. The aggregation may be due to the presence of phytochemicals from Moringa oleifera leaf extract, which act as reducing and stabilizing agents. The porous morphology observed in the image suggests a high surface area, which is beneficial for antimicrobial and catalytic applications. Similar observations have been reported by Dauthal and Mukhopadhyay (2016) and Mourdikoudis et al. (2018).

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TEM Analysis :-

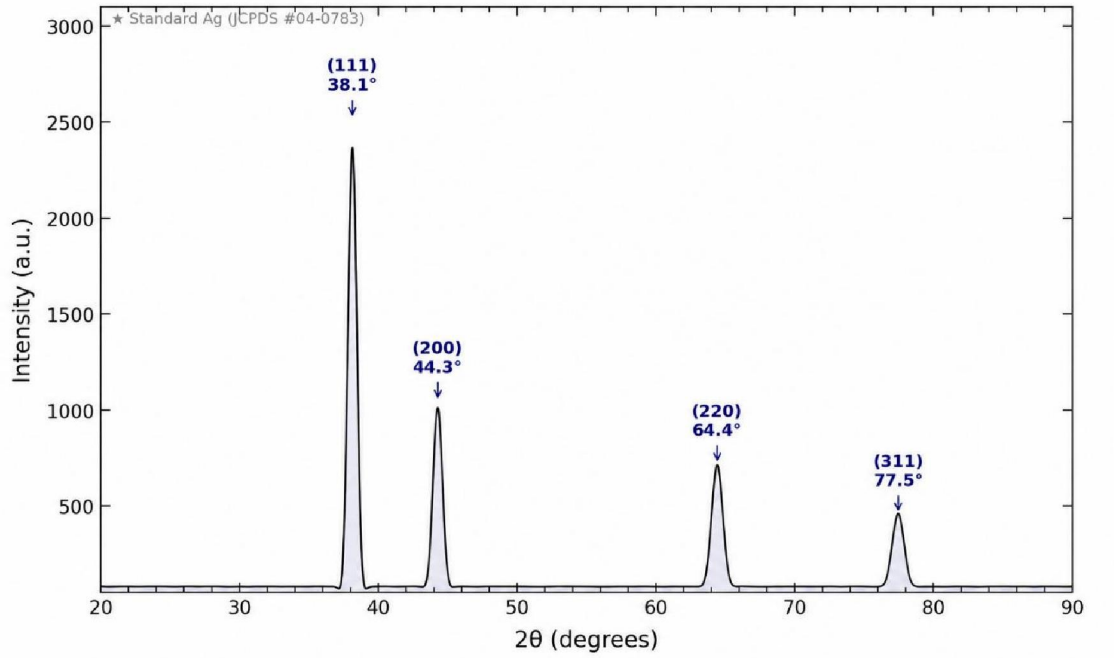
TEM Analysis Transmission Electron Microscopy (TEM) was employed to determine the size and shape of the synthesized silver nanoparticles. The TEM image showed that the nanoparticles were predominantly spherical to nearly spherical in shape and distributed within the nanometer range. Some particles appeared slightly aggregated, while most nanoparticles were clearly distinguishable. The dark spots in the image represent silver nanoparticles. The observed morphology confirms the successful reduction of silver ions and formation of nanosized particles. These results are in agreement with the findings reported by Khan et al. (2019) and Mourdikoudis et al. (2018).



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XRD Analysis :-

XRD Analysis X-Ray Diffraction (XRD) analysis was performed to determine the crystalline nature and structural properties of the synthesized silver nanoparticles. The XRD pattern showed distinct diffraction peaks at 38.1°, 44.3°, 64.4°, and 77.5°, corresponding to the crystal planes (111), (200), (220), and (311), respectively. These peaks are characteristic of metallic silver and match the standard silver diffraction data (JCPDS No. 04-0783). The presence of sharp and intense peaks confirms the crystalline nature of the synthesized nanoparticles. The highest intensity peak observed at 38.1° corresponding to the (111) plane indicates the preferred orientation of silver crystals. Furthermore, the absence of additional impurity peaks suggests the high purity of the synthesized silver nanoparticles. Therefore, the XRD results confirm the successful formation of crystalline silver nanoparticles with a face-centered cubic (FCC) crystal structure.



Silver nanoparticles (AgNPs) have gained significant attention in water treatment technologies due to their excellent antimicrobial and catalytic properties. According to Roy et al. (2010), silver nanoparticles effectively inhibit the growth of harmful microorganisms, including bacteria, fungi, and viruses present in contaminated water. Their large surface area and high reactivity enhance their efficiency in disinfection processes. Khan et al. (2019) reported that AgNPs can be incorporated into filtration systems and membranes to improve water quality by removing microbial contaminants and reducing waterborne diseases. Therefore, silver nanoparticles are considered promising materials for the development of advanced water purification systems.

Nanotechnology has emerged as an effective approach for controlling environmental pollution. Silver nanoparticles possess unique catalytic and adsorptive properties that enable the degradation of various pollutants present in air, water, and soil. Veisi et al. (2018) reported that green-synthesized nanoparticles can be utilized for the removal of toxic chemicals, dyes, and organic contaminants from industrial wastewater. The high surface reactivity of nanoparticles facilitates interactions with pollutants, leading to their degradation or transformation into less harmful substances. Furthermore, Khan et al. (2019) emphasized that nanoparticle-based technologies offer sustainable and efficient solutions for reducing environmental pollution and improving ecosystem health.

Environmental remediation involves the removal or neutralization of pollutants from contaminated environments. Silver nanoparticles have shown considerable potential in remediation applications due to their antimicrobial, catalytic,

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and adsorption capabilities. According to Roy et al. (2010), nanoparticles can assist in the treatment of contaminated water and soil by eliminating pathogenic microorganisms and degrading hazardous compounds. Veisi et al. (2018) highlighted that biosynthesized nanoparticles are environmentally friendly and suitable for remediation processes because they are produced using natural biological resources. Additionally, Khan et al. (2019) reported that nanoparticle based remediation technologies can contribute to sustainable environmental management by enhancing pollutant removal efficiency and minimizing ecological risks.

V. CONCLUSION

Nanotechnology has emerged as a rapidly growing field with significant applications in medicine, biotechnology, environmental science, and industry. Among various nanomaterials, silver nanoparticles (AgNPs) have attracted considerable attention due to their unique physicochemical, antimicrobial, catalytic, and biomedical properties. The present study focused on the green synthesis of silver nanoparticles using Moringa oleifera leaf extract as a natural reducing and stabilizing agent. Moringa oleifera is rich in bioactive phytochemicals such as flavonoids, phenolic compounds, tannins, proteins, and antioxidants, which play an important role in the reduction of silver ions and stabilization of nanoparticles. The use of plant extract provides an eco-friendly, cost-effective, and sustainable alternative to conventional physical and chemical synthesis methods. Green synthesis minimizes the use of hazardous chemicals and supports the principles of green chemistry. The synthesized silver nanoparticles were successfully characterized using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD) techniques. These characterization studies confirmed the successful formation of silver nanoparticles with desirable morphology, nanoscale dimensions, and crystalline structure. Silver nanoparticles exhibit remarkable biological activities, particularly antimicrobial properties, making them useful in healthcare and biomedical applications. In addition, they have significant environmental applications in water purification, pollution control, and environmental remediation due to their catalytic and antimicrobial capabilities. The growing demand for sustainable technologies further highlights the importance of green-synthesized nanoparticles.

Future advancements in this field may lead to the development of novel applications in wound healing, targeted drug delivery, cancer therapy, biosensors, food packaging, agriculture, wastewater treatment, and environmental protection. Therefore, the green synthesis of silver nanoparticles using Moringa oleifera leaf extract represents a promising, environmentally sustainable, and scientifically valuable approach with broad applications in modern nanotechnology and biomedical research.

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