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Synthesis of Silver Nanoparticles Using Seaweeds: A Review

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Abstract

Nanotechnology has become an important field with applications in medicine, agriculture, environmental remediation, food technology, and pharmaceuticals. Among nanomaterials, silver nanoparticles (AgNPs) have received considerable attention due to their unique physicochemical properties and diverse biological activities. Conventional synthesis methods often involve toxic chemicals and high energy consumption, creating environmental concerns. Therefore, green synthesis approaches have emerged as sustainable alternatives. Seaweeds (marine macroalgae) are promising resources for the eco-friendly synthesis of AgNPs because they contain bioactive compounds such as polysaccharides, proteins, phenolics, flavonoids, pigments, and vitamins that act as natural reducing and stabilizing agents.Recent studies have reported the successful synthesis of silver nanoparticles using extracts from green, brown, and red seaweeds. These nanoparticles exhibit significant antimicrobial, antioxidant, anticancer, anti-inflammatory, and catalytic activities. Characterization techniques including UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, and DLS are commonly used to confirm nanoparticle formation and evaluate their physicochemical properties. Seaweed-mediated synthesis offers advantages such as simplicity, cost-effectiveness, environmental friendliness, and scalability. This review highlights recent advances in seaweed-based AgNP synthesis, mechanisms of nanoparticle formation, characterization methods, biological activities, and industrial applications. It also discusses challenges and future prospects for large-scale production and commercialization, emphasizing the role of marine bioresources in sustainable nanotechnology.

1. Introduction

Nanotechnology is a multidisciplinary field that involves the design, synthesis, characterization, and application of materials at the nano scale level, typically ranging from 1 to 100 nm (Drexler, 1986). Nano particles possess unique physical, chemical, optical, and biological properties compared to their bulk counterparts due to their high surface area-to-volume ratio and quantum confinement effects (Roco, 2003). These distinctive characteristics have led to their widespread use in biomedical sciences, environmental engineering, electronics, agriculture, food preservation, and pharmaceutical industries.

Among the various metallic nanoparticles, silver nanoparticles (AgNPs) are one of the most extensively studied nanomaterials because of their remarkable antimicrobial, antioxidant, anti-inflammatory, anticancer, and catalytic properties (Rai *et al.,* 2009; Ahmed *et al.,* 2016). Their effectiveness against a broad range of microorganisms has resulted in applications in wound dressings, drug delivery systems, medical devices, food packaging, and water purification technologies.

Traditional methods for synthesizing silver nanoparticles include physical and chemical approaches. Physical methods often require expensive instrumentation and high energy consumption, whereas chemical methods frequently employ toxic reducing agents and stabilizers that may pose risks to both human health and the environment (Iravani, 2011). These limitations have encouraged the development of environmentally friendly and sustainable alternatives for nanoparticle synthesis.

Green synthesis has emerged as an attractive strategy that utilizes biological resources such as plants, fungi, bacteria, algae, and seaweeds as reducing and capping agents (Shankar *et al.,* 2004). Biological synthesis eliminates the need for hazardous chemicals and provides a cost-effective and eco-friendly approach to nanoparticle production.

Seaweeds are marine macroalgae that occur abundantly in coastal ecosystems and are classified into green algae (Chlorophyta), brown algae (Phaeophyta), and red algae (Rhodophyta) (Lee, 2008). These marine organisms are rich sources of bioactive compounds including polysaccharides, proteins, amino acids, polyphenols, flavonoids, pigments, vitamins, and minerals (Holdt and Kraan, 2011). Such compounds play a vital role in the reduction of silver ions into metallic nanoparticles and simultaneously stabilize the synthesized nanoparticles by preventing aggregation.

Numerous studies have reported the successful synthesis of silver nanoparticles using seaweed extracts and have demonstrated their diverse biological activities, including antimicrobial, antioxidant, anticancer, and catalytic effects (Vijayaraghavan *et al.,* 2012; Rajathi *et al.,* 2012). The synthesized nanoparticles are typically characterized using analytical techniques such as UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, and DLS to determine their size, morphology, crystallinity, and surface chemistry (Mourdikoudis *et al.,* 2018).

The present review aims to provide a comprehensive overview of seaweed-mediated synthesis of silver nanoparticles, including the underlying synthesis mechanisms, characterization techniques, biological activities, applications, and future research directions. The review highlights the potential of seaweeds as sustainable resources for nanoparticle production and their role in advancing green nanotechnology.

2. Methodology

2.1 Literature Search Strategy

A comprehensive literature search was conducted to collect published research articles related to the green synthesis of silver nanoparticles using seaweeds. Relevant scientific literature published between 2000 and 2025 was retrieved from major electronic databases including Google Scholar, PubMed, ScienceDirect, Scopus, SpringerLink, and Web of Science. Keywords used for the search included "silver nanoparticles", "green synthesis", "seaweed-mediated synthesis", "marine algae nanoparticles", "biosynthesis of silver nanoparticles", and "nanotechnology applications".

2.2 Inclusion and Exclusion Criteria

Studies were selected based on their relevance to seaweed-mediated synthesis of silver nanoparticles. Research articles reporting the synthesis, characterization, biological activities, and applications of silver nanoparticles using seaweed extracts were included. Review articles, conference papers, book chapters, and studies unrelated to seaweed-based nanoparticle synthesis were excluded from detailed analysis.

Inclusion Criteria

- Articles published in peer-reviewed journals.
- Studies focusing on seaweed-mediated synthesis of silver nanoparticles.
- Research reporting characterization and biological activities of synthesized nanoparticles.
- Publications written in English.

Exclusion Criteria

- Studies involving nanoparticles synthesized using non-seaweed biological sources.
- Duplicate publications.
- Articles with incomplete experimental data.
- Non-English publications.

2.3 Data Collection and Extraction

Relevant information was extracted from the selected studies, including:

- Seaweed species used for nanoparticle synthesis.
- Method of extract preparation.
- Silver nitrate concentration.
- Synthesis conditions.
- Characterization techniques employed.
- Particle size and morphology.
- Biological activities reported.
- Potential applications of synthesized nanoparticles.

The extracted information was organized systematically and compared across different studies.

2.4 Data Analysis

The collected literature was critically analyzed to identify trends, similarities, and differences among various seaweed-mediated synthesis methods. Particular emphasis was placed on synthesis mechanisms, characterization results, antimicrobial activity, antioxidant properties, and industrial applications. Findings from different studies were summarized using tables, figures, and graphical representations to facilitate comparison.

3. Results and Discussion

3.1 Seaweed Species Used for Silver Nanoparticle Synthesis

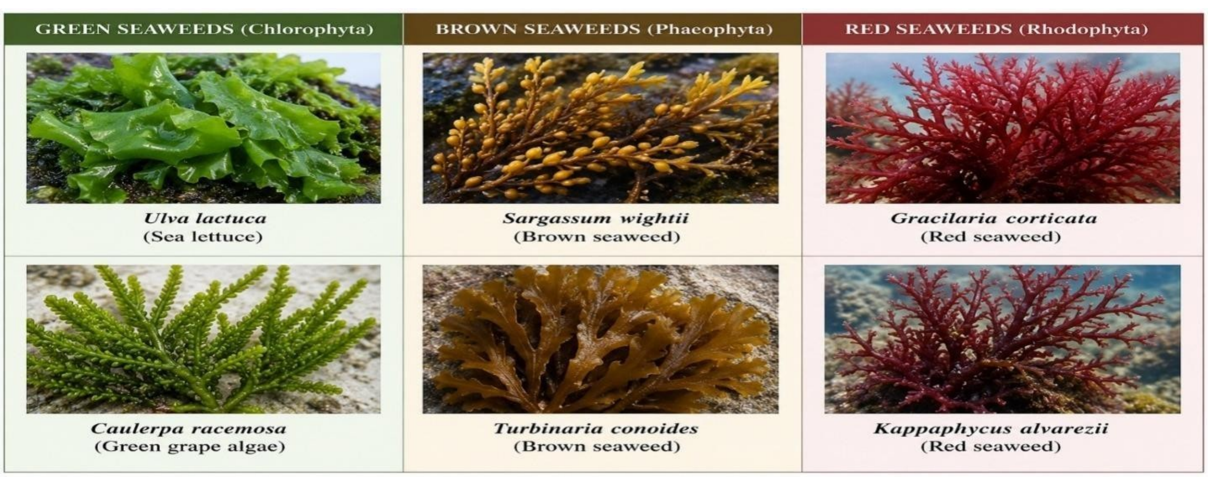
Numerous seaweed species belonging to the green, brown, and red algae groups have been successfully employed for the biosynthesis of silver nanoparticles. Seaweed extracts contain polysaccharides, proteins, polyphenols, flavonoids, and pigments that act as reducing and stabilizing agents during nanoparticle formation (Holdt and Kraan, 2011; Vijayaraghavan *et al.*, 2012).

Table 1. Common Seaweed Species Used for Silver Nanoparticle Synthesis

Seaweed Species	Algal Group	Average Particle Size (nm)	Reference
Sargassum wightii	Brown algae	10–50	Vijayaraghavan *et al.,* 2012
Turbinaria conoides	Brown algae	15–60	Rajathi *et al.,* 2012
Ulva lactuca	Green algae	20–80	Rajeshkumar and Malarkodi, 2014
Gracilaria corticata	Red algae	10–70	Vivek *et al.,* 2011
Padina tetrastromatica	Brown algae	15–55	Govindaraju *et al.,* 2009

Brown seaweeds, particularly *Sargassum* and *Turbinaria* species, are frequently reported for silver nanoparticle synthesis because of their high content of polysaccharides and phenolic compounds. Most synthesized nanoparticles ranged from 10–80 nm in size, indicating effective nanoparticle formation.

Figure 1. Representative seaweed species used in silver nanoparticle synthesis



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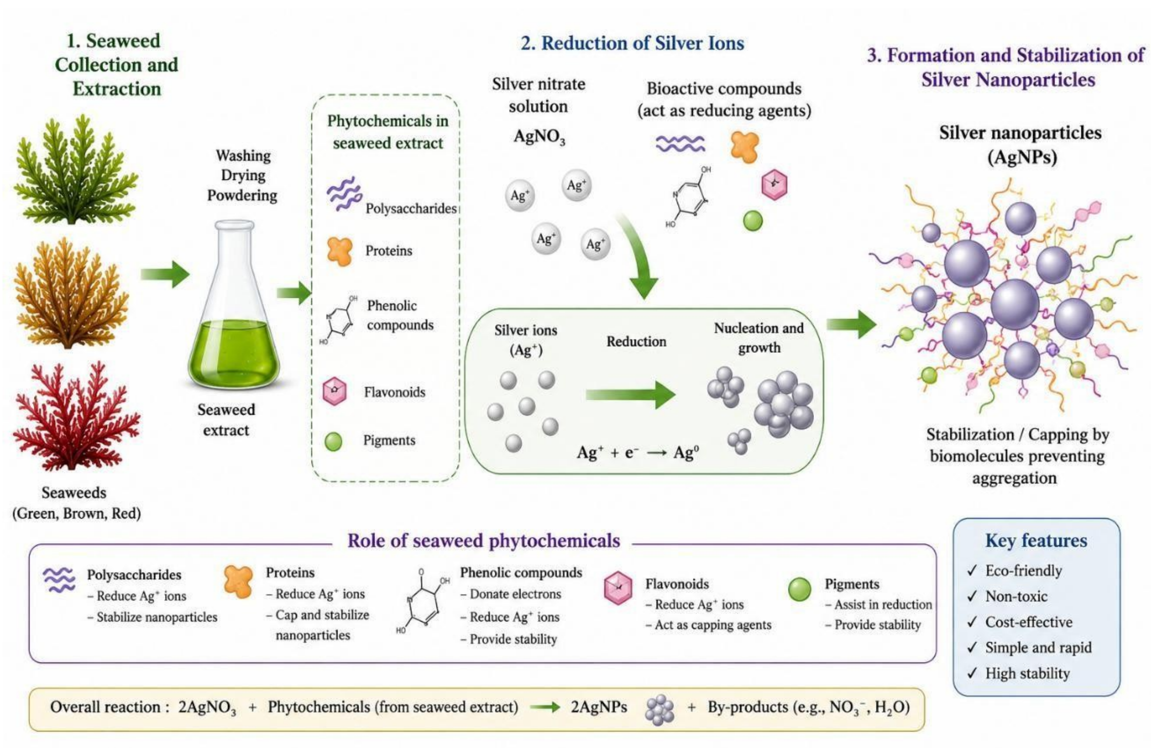
3.2 Mechanism of Seaweed-Mediated Silver Nanoparticle Synthesis

The synthesis process involves the reduction of silver ions (Ag^+) to metallic silver nanoparticles (Ag^0) by bioactive compounds present in seaweed extracts. Simultaneously, these compounds act as capping agents, stabilizing the nanoparticles and preventing aggregation (Rajathi *et al.,* 2012).

Figure 2. Mechanism of silver nanoparticle synthesis using seaweed extract



Polysaccharides, proteins, flavonoids, and phenolic compounds are primarily responsible for the reduction and stabilization process. This mechanism makes seaweed-mediated synthesis environmentally friendly and sustainable.

3.3 Characterization of Synthesized Silver Nanoparticles

Various analytical techniques have been employed to confirm nanoparticle synthesis and evaluate their physicochemical properties.

Table 2. Characterization Techniques Used for Silver Nanoparticles

Technique	Purpose	Typical Observation
UV–Visible Spectroscopy	Confirmation of nanoparticle formation	SPR peak at 400–450 nm
FTIR	Functional group identification	O–H, C=O, C–N peaks
XRD	Crystallinity analysis	Characteristic silver diffraction peaks
SEM	Morphology determination	Spherical nanoparticles
DLS	Particle size analysis	10–100 nm range

UV–Visible spectroscopy consistently shows surface plasmon resonance peaks around 400–450 nm, confirming silver nanoparticle formation. FTIR studies indicate the involvement of proteins and phenolic compounds in nanoparticle stabilization. XRD confirms the crystalline nature of silver nanoparticles, while SEM and DLS provide information regarding morphology and particle size distribution.

3.4 Biological Activities of Seaweed-Derived Silver Nanoparticles

Silver nanoparticles synthesized using seaweeds exhibit significant biological activities including antimicrobial, antioxidant, anticancer, and anti-inflammatory properties (Rai *et al.,* 2009; Ahmed *et al.,* 2016).

Most studies reported strong antimicrobial activity against both Gram-positive and Gram-negative bacteria. The antimicrobial effect is attributed to nanoparticle interaction with bacterial cell membranes, leading to cellular damage and death.

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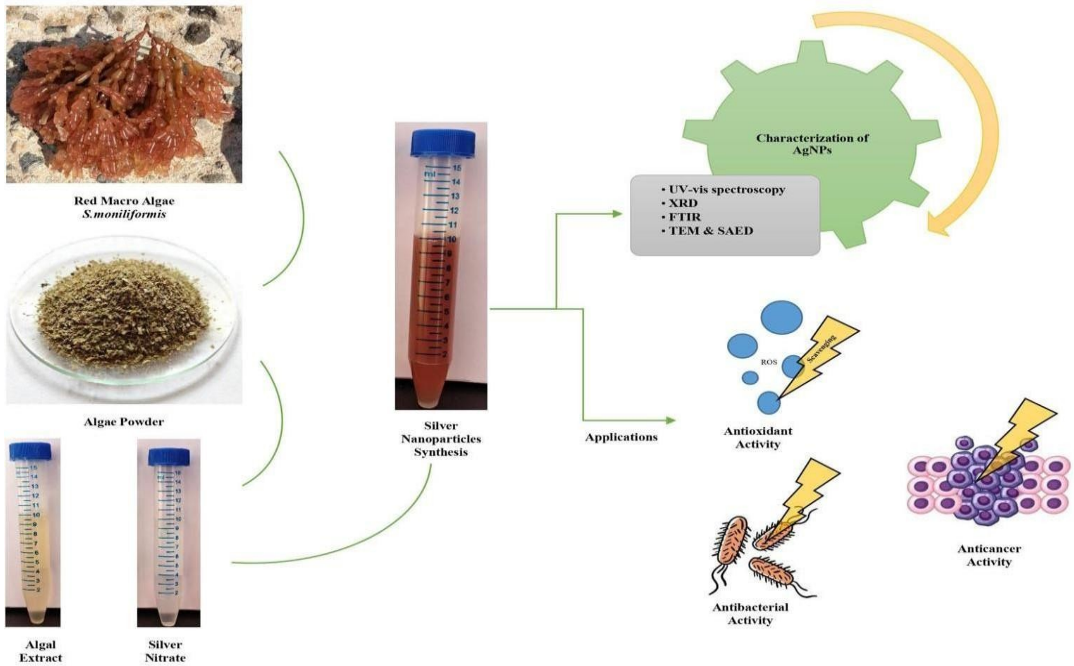
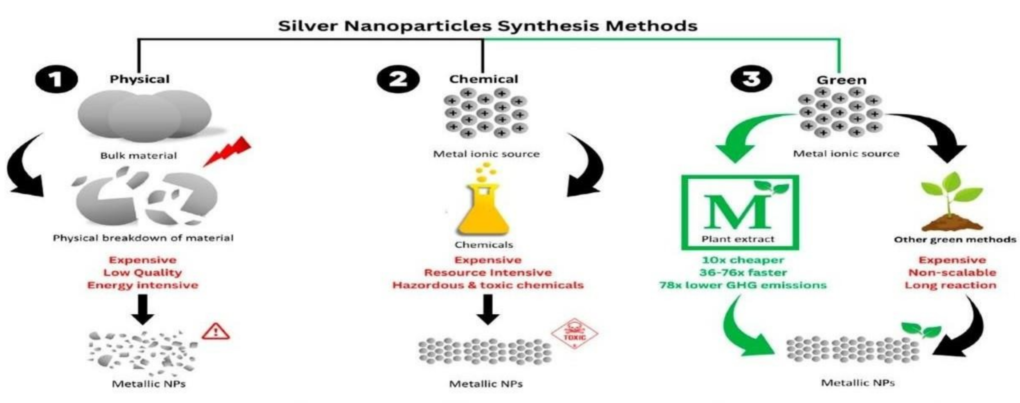
Figure 3. Antimicrobial activity of seaweed-derived silver nanoparticles



3.5 Applications of Seaweed-Synthesized Silver Nanoparticles

Seaweed-mediated silver nanoparticles have diverse applications in medicine, food preservation, agriculture, wastewater treatment, and pharmaceutical industries (Marambio-Jones and Hoek, 2010).

Figure 4. Industrial applications of seaweed-mediated silver nanoparticles



Biomedical applications represent the largest area of research, followed by food preservation and environmental remediation. The increasing number of studies highlights the growing importance of seaweed-derived nanoparticles in sustainable nanotechnology.

4. Summary and Conclusion

The present review highlights the significant advancements in the green synthesis of silver nanoparticles (AgNPs) using seaweed extracts and their potential applications in various fields. Nanotechnology has emerged as an important interdisciplinary field, and silver nanoparticles have gained considerable attention because of their unique physicochemical and biological properties. Compared with conventional physical and chemical methods, seaweed-mediated synthesis offers a sustainable, eco-friendly, cost-effective, and efficient approach for nanoparticle production.

Seaweeds are rich sources of biologically active compounds such as polysaccharides, proteins, amino acids, phenolic compounds, flavonoids, pigments, vitamins, and minerals. These biomolecules function as natural reducing, stabilizing, and capping agents during nanoparticle synthesis, eliminating the need for hazardous chemicals. The review demonstrates that various species of green, brown, and red algae have been successfully utilized for the synthesis of silver nanoparticles with different sizes, morphologies, and biological activities.

Characterization studies using UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, and DLS have confirmed the successful formation of stable and crystalline silver nanoparticles. UV–Visible spectroscopy is widely used to identify nanoparticle formation through characteristic surface plasmon resonance peaks, while FTIR analysis provides information regarding the functional groups involved in nanoparticle stabilization. XRD analysis confirms crystallinity, whereas SEM, TEM, and DLS reveal nanoparticle morphology and size distribution.

The review also emphasizes the broad spectrum of biological activities exhibited by seaweed-derived silver nanoparticles. Numerous studies have reported strong antimicrobial activity against pathogenic bacteria and fungi, making these nanoparticles promising candidates for medical and pharmaceutical applications. Additionally, antioxidant, anticancer, anti-inflammatory, and catalytic properties have been extensively documented. These characteristics support their application in wound healing, drug delivery systems, food packaging, water purification, agriculture, and environmental remediation.

Despite the promising outcomes, several challenges remain regarding large-scale production, standardization of synthesis protocols, reproducibility, nanoparticle stability, and toxicity assessment. Future research should focus on optimizing synthesis conditions, understanding molecular mechanisms, evaluating long-term safety, and developing industrial-scale production methods. Furthermore, advanced analytical techniques and interdisciplinary research approaches are required to enhance the commercial potential of seaweed-mediated silver nanoparticles.

In conclusion, seaweed-based synthesis of silver nanoparticles represents a sustainable and environmentally friendly strategy for nanoparticle production. The abundance of marine resources, coupled with their rich phytochemical composition, makes seaweeds highly suitable for green nanotechnology applications. Continued research in this area will contribute significantly to the development of innovative nanomaterials for biomedical, environmental, agricultural, and industrial applications while promoting sustainable utilization of marine bioresources.

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