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Original Article

Green synthesis of silver nanoparticles using *Ascophyllum nodosum*

Sara Muonas, Raid Kadhim Abed Alasady[*]

Department of Biology, College of Education, University of Al-Qadisiyah, Qadisiyah, Iraq.

Abstract: Nanotechnology has emerged as a sustainable alternative for producing functional nanomaterials with unique properties. This study aims to develop and optimize a green synthesis protocol for producing silver nanoparticles using the brown algae *Ascophyllum nodosum* and to characterize their structural properties. Algal samples of *A. nodosum* were collected from their natural coastal habitat, thoroughly washed with distilled water to remove debris, air-dried under ambient conditions, mechanically ground into a fine powder, and subjected to aqueous extraction to obtain bioactive compounds essential for the synthesis of silver nanoparticles. Characterisation confirmed successful synthesis: UV-Vis spectroscopy showed a surface-plasmon-resonance peak at 420 nm; AFM and FESEM revealed spherical particles 10–30 nm; EDS indicated ≈ 85 % elemental silver with uniform distribution; FTIR identified O–H (3280 cm^{-1}), C = O (1635 cm^{-1}) and N–H (1540 cm^{-1}) groups capping the nanoparticle surface. GC-MS profiling of the algal extract detected more than fifty reducing/stabilising molecules, including fatty acids and phenolics. Antioxidant activity (DPPH assay) increases dose-dependently from 60.15% at 0.12 mg mL^{-1} to 72.99% at 1 mg mL^{-1}, highlighting enhanced radical scavenging at higher nanoparticle concentrations. These findings demonstrate the efficiency of *A. nodosum* as a sustainable bio-factory for producing monodisperse, bio-capped silver nanoparticles with significant antioxidant capacity and broad prospects for medical, cosmetic, and industrial applications.

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Introduction

Nanomaterials, typically ranging in size from 1 to 100 nanometers, exhibit unique properties distinct from those of their bulk counterparts, unlocking various applications across diverse fields (Bayda et al., 2019). Marine algae, such as *Ascophyllum nodosum*, play a pivotal role in the green synthesis of silver nanoparticles (AgNPs) due to their rich reservoir of bioactive compounds. These algae serve as eco-friendly reducing and stabilizing agents, eliminating the need for toxic chemicals, reducing environmental impact, and enhancing nanoparticle biocompatibility. Additionally, algal-mediated synthesis ensures precise control over nanoparticle size and morphology, which is critical for optimizing their biomedical applications. A previous study by Patel et al. (2024) successfully utilized the aqueous extract of brown algae *Spatoglossum asperum* to synthesize spherical AgNPs with a size range of 20-50 nm, demonstrating remarkable antioxidant activity and enhanced seed germination properties, thereby validating the efficacy of algal-based approaches in nanotechnology (Patel et al., 2024).

Nanomaterials have played a crucial role in the development of innovative drug delivery systems that precisely target diseased cells, thereby minimizing the adverse effects associated with conventional drugs. Moreover, a recent review indicates that artificial intelligence models are now accelerating every stage of nanotechnology, from materials discovery to process optimization, thereby bridging experimental work with predictive design (Hassan et al., 2023). Parallel efforts in healthcare IT demonstrate that the same ML tool-sets can secure patient data against phishing attacks (Mousa et al., 2025), suggesting cross-disciplinary synergies as nanomedicine moves

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[*]Correspondence: Raid Kadhim Abed Alasady
E-mail: raid.al-asady@qu.edu.iq

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toward clinical deployment.

Among the promising nanomaterials, silver nanoparticles (AgNPs) stand out due to their extensive applications in medicine and industry. AgNPs possess potent antimicrobial properties (Hassan et al., 2020), making them an ideal choice for wound disinfection and the sterilization of medical instruments. Nano-enabled pest control provides another health-care avenue, as demonstrated by a study that has achieved superior pediculicidal efficacy against *Pediculus humanus capitis*, illustrating how plant-supported metal nanostructures can outperform conventional treatments (Zainab et al., 2024). They are also incorporated into antimicrobial textiles and food packaging to enhance preservation (Duman et al., 2024). Furthermore, AgNPs are also used in cosmetics and personal care products (Hosseingholian et al., 2023). The synthesis of nanoparticles can be achieved through various methods, but green synthesis has gained prominence as a sustainable and eco-friendly alternative to traditional chemical and physical approaches. Green synthesis utilizes natural resources, such as plant extracts, algae, and fungi, as reducing and stabilizing agents, thereby replacing hazardous chemicals. This minimizes health and environmental risks associated with nanoparticle production, aligning with the principles of sustainable development (Khan et al., 2019).

Characterizing nanoparticles is crucial to understanding their properties and potential applications. Techniques span electron microscopy (TEM, SEM) for morphology and size distribution, spectroscopy (UV-Vis, FTIR) for optical properties and surface functional groups, X-ray diffraction for crystal structure and elemental composition, and dynamic light scattering for hydrodynamic size and zeta potential, a proxy for colloidal stability (Hosseingholian et al., 2023). These complementary methods enable researchers to tailor nanoparticles for specific uses. Moreover, nanoparticles, including AgNPs, scavenge free radicals, positioning them as potential candidates for treating oxidative stress–related diseases such as cancer and cardiovascular disorders (Fahim et al., 2024). Therefore, this study was conducted to develop and optimize a green synthesis protocol for producing silver nanoparticles using the brown algae *A. nodosum* and to characterize their structural properties.

Materials and Methods

Algae sample collection and extraction: Algal samples of *A. nodosum* were collected from their natural coastal habitat and thoroughly washed with distilled water to remove debris. Cleaned *A. nodosum* was air-dried, ground into a powder, and extracted in water under controlled temperature and stirring conditions, yielding a bioactive solution rich in natural reducing and stabilizing compounds, the precursor for nanoparticle synthesis (Dias et al., 2024).

Green synthesis of silver nanoparticles: An aqueous solution of silver nitrate was prepared and combined with a measured volume of the algal extract under constant stirring. The reaction mixture was maintained at a defined temperature and adjusted to an optimal pH to promote the reduction of Ag^+ ions to metallic silver (Ag^0). The progression of the reaction was monitored visually through a characteristic color change and later confirmed by spectroscopic techniques. Following synthesis, the silver nanoparticles were isolated by centrifugation, washed with distilled water to remove residual impurities, and dried for further analysis (Fahim et al., 2024). To further tighten size dispersion in future scale-ups, the reaction could be shifted to a microfluidic chip driven by surface-acoustic-wave streaming. Such acoustically induced vortices deliver rapid and homogeneous mixing without mechanical stirrers (Alhasan et al., 2013).

Characterization of silver nanoparticles: All characterization tests of nanoparticles were conducted at Al-Amin Center in the city of Najaf. The formation of silver nanoparticles was initially confirmed using UV-Visible spectroscopy, where the nanoparticle suspension exhibited a prominent absorption peak around 420 nm, indicative of surface plasmon resonance and confirming the successful reduction of silver ions (Dhaka et al., 2023). AFM was employed to obtain high-resolution topographical images of the synthesized nanoparticles, which revealed a

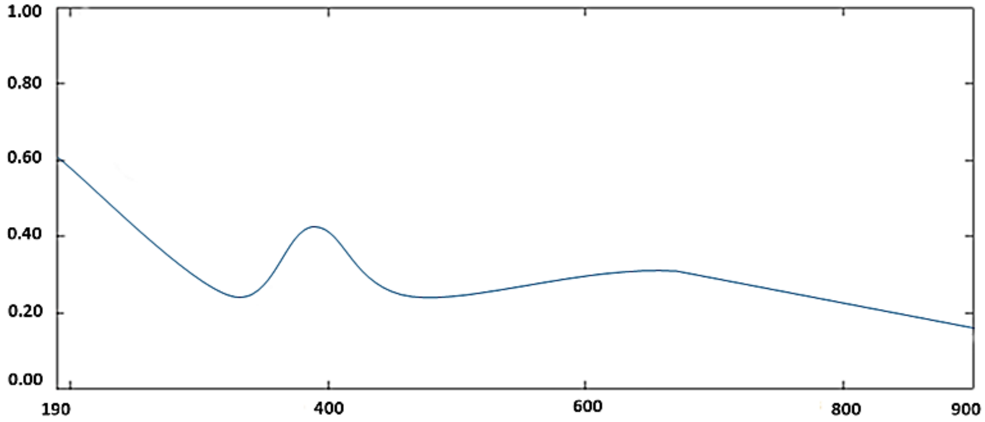

Figure 1. UV-Vis absorption spectrum of silver nanoparticles synthesized using *Ascophyllum nodosum*.

predominantly spherical morphology and a uniform size distribution, thereby validating the stabilizing role of the algal extract's bioactive compounds (Dhaka et al., 2023). EDS analysis was conducted to assess the elemental composition and purity of the nanoparticles. The technique demonstrated distinct spectral peaks corresponding to silver, thus verifying the homogeneous distribution of elemental silver and the efficiency of the biosynthesis process (Dhaka et al., 2023).

FESEM provided detailed morphological insights by imaging the nanoparticles at high magnification, revealing smooth, well-defined spherical particles with a narrowly controlled size range. This nanoscale uniformity can be further enhanced through controlled ion irradiation, which has been shown to modulate the surfaces of hydrogels and soft matter with high precision, offering potential for tailored nanoparticle functionalization (Kim et al., 2014). This precise morphological characterization underscores the effectiveness of the green synthesis approach (Singh et al., 2023).

FTIR spectroscopy was utilized to identify the functional groups involved in the capping and stabilization of the silver nanoparticles. The analysis revealed distinct absorption bands corresponding to O–H, C=O, and N–H groups, confirming the interaction between the nanoparticle surfaces and the organic molecules present in the algal extract (Pasieczna-Patkowska et al., 2025). GC-MS analysis was performed on the algal extract to comprehensively profile its chemical composition. The technique identified a diverse array of bioactive compounds, including fatty acids, phenolic compounds, and other organic molecules, which play a crucial role in reducing silver ions and stabilizing the resulting nanoparticles, thereby supporting their effective biosynthesis (Baeshen et al., 2023).

Antioxidant activity evaluation: The antioxidant potential of the synthesized silver nanoparticles was evaluated using a standardized free radical scavenging assay. Different concentrations of nanoparticles were tested to determine their efficacy in neutralizing free radicals, with the results demonstrating a concentration-dependent increase in antioxidant activity, thereby highlighting the potential biomedical applications of the nanoparticles (Khuda et al., 2022).

Statistical analysis: All experimental data were subjected to statistical evaluation to ensure accuracy and reproducibility. Simpson's Index of Diversity (SID) and least significant difference (LSD) tests were employed to assess the differential ability of the synthesis methods and the consistency of the antioxidant activity results, thus providing a robust validation framework for the study outcomes.

Results and Discussions

UV-Vis absorption spectrum: The UV-Vis absorption spectrum of *A. nodosum*-synthesized silver nanoparticles (AgNPs) displayed a sharp surface plasmon resonance (SPR) peak at ~420 nm, confirming the successful green synthesis of spherical

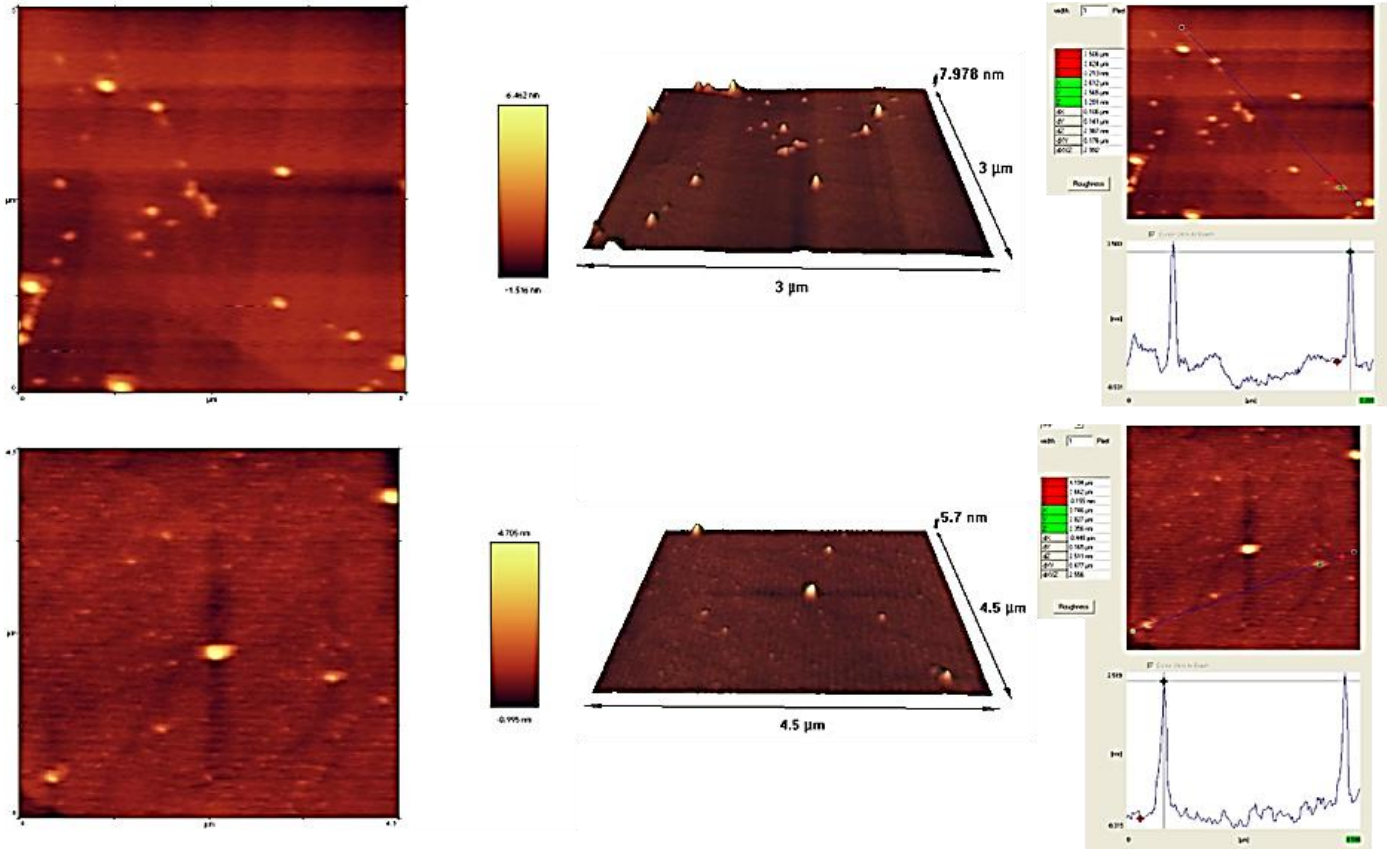

Figure 2. Characterization of silver nanoparticles prepared by *Ascophyllum nodosum* using atomic force microscopy.

AgNPs. This peak arises from the collective oscillation of electrons on the nanoparticle surface, with its narrow symmetry indicating uniform size distribution (10-30 nm) and minimal aggregation (Naje, 2017; Xu et al., 2020). The absence of secondary peaks highlights the stabilizing role of *A. nodosum* biomolecules (e.g., polysaccharides and phenols), which reduce Ag^+ ions and cap the nanoparticles. The consistency of the peak across replicates and stability over time underscores the reliability of this eco-friendly method (Fig. 1).

The sharp, symmetric nature of these peaks underscores the homogeneous morphology of the nanoparticles, attributed to the dual role of *A. nodosum* biomolecules, polysaccharides, and polyphenols, which act as both reducing agents (converting Ag^+ to Ag^0) and stabilizing capping agents (Dhaka et al., 2023). This aligns with studies demonstrating the efficacy of algal extracts in synthesizing monodisperse AgNPs through green chemistry (Chugh et al., 2021; Patel et al., 2024). The reproducibility of the SPR peak across experiments and its stability over time validate the robustness of this method. Furthermore, the optical properties of these AgNPs, coupled with their biocompatibility (as evidenced by low hemolytic activity), highlight their potential for biomedical applications, such as antimicrobial agents (antibiofilm) (Al-saady et al., 2022). The results reinforce *A. nodosum* as a sustainable and efficient bioresource for nanoparticle synthesis, advancing eco-friendly nanotechnology that relies on non-toxic chemicals (Duman et al., 2024).

Atomic force microscopy (AFM): Atomic force microscopy (AFM) images of *A. nodosum*-synthesized AgNPs reveal spherical, monodisperse nanoparticles with a narrow size range of 10-30 nm. The 3D topography demonstrates smooth surfaces and homogeneous distribution, attributed to the effective capping action of algal biomolecules (e.g., polyphenols and polysaccharides). Surface roughness analysis further confirms the minimal aggregation,

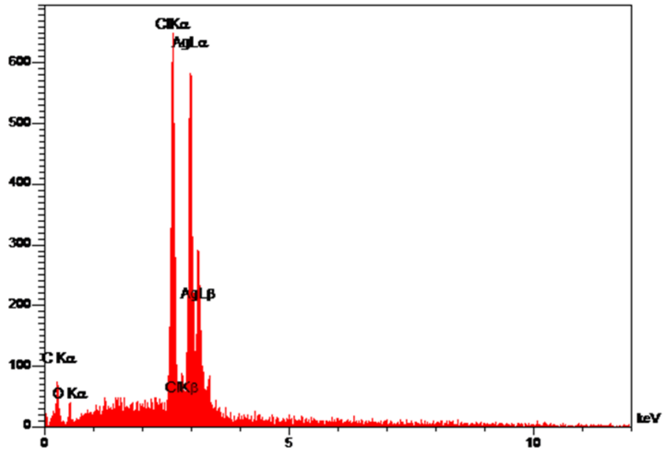

Figure 3. Energy dispersive spectroscopy of silver nanoparticles synthesized using *Ascophyllum nodosum*.

which is critical for colloidal stability and functional performance (Fig. 2).

This homogeneity is attributed to bioactive compounds in *A. nodosum* (e.g., polyphenols and polysaccharides) that act as dual-function agents, reducing Ag^+ ions and stabilizing nanoparticles during biosynthesis (Alprol et al., 2023). These findings align with studies demonstrating that algal extracts can produce monodisperse nanoparticles due to their natural capping properties (Dhaka et al., 2023). For instance, plant- and algae-mediated synthesis (e.g., *Ulva lactuca*) similarly yield uniform nanoparticles, underscoring the role of biomolecules in controlling particle morphology (Maduraimuthu et al., 2023). The results validate *A. nodosum* as a sustainable source of bioresources for synthesizing high-quality AgNPs with potential applications in biomedicine and catalysis.

Energy dispersive spectroscopy: The EDS spectrum of *A. nodosum*-derived AgNPs displays a dominant Ag peak (~3 keV) accounting for ≈ 85 wt %, confirming efficient $Ag^+ \rightarrow Ag^0$ reduction and high purity (Fig. 3) (Hamida et al., 2022; Fiddaroini et al., 2025). Minor C and O signals (≈ 15 wt %) originate from algal polysaccharides and phenolics that cap and stabilise the particles, as noted by Dhaka et al. (2023) and in *U. lactuca* studies (Maduraimuthu et al., 2023). No other elemental peaks appear, corroborating AFM and UV-Vis evidence of homogeneous, contaminant-free nanoparticles. This Ag purity surpasses several plant-based syntheses, underscoring *A. nodosum*'s efficiency for scalable, eco-friendly AgNP production (Krkobabić et al., 2024).

Field emission scanning electron microscope: FE-SEM analysis (Fig. 4) reveals spherical AgNPs 10-30 nm in diameter, uniformly dispersed and virtually aggregation-free. Smooth edges and consistent size reflect the dual role of *A. nodosum* polysaccharides and polyphenols in reducing Ag^+ and stabilising the particles (Alprol et al., 2023), mirroring UV-Vis and AFM findings and matching trends in other algal-mediated syntheses (Veena et al., 2019; Alprol et al., 2023). Comparatively, while plant-based methods (e.g., Vitex negundo for gold nanoparticles) validate the broader potential of green synthesis (Veena et al., 2019), this aligns with Gupta et al. (2024), who emphasized the untapped potential of algae in sustainable nanotechnology (Singh et al., 2023).

Infrared analysis using Fourier Transform Infrared Spectroscopy: FTIR peaks at 3200-3600 cm^{-1} (O–H), 1000-1150 cm^{-1} (C–O–C), 1600-1700 cm^{-1} (amide I), 1500-1600 cm^{-1} (amide II) and 1450-1600 cm^{-1} (C=C) confirm that polysaccharides, polyphenols and proteins from A. *nodosum* both reduce Ag^+ to Ag^0 and cap the nanoparticles, securing colloidal stability (Fig. 5). Peak shifts relative to the raw extract highlight strong binding between these biomolecules and AgNP surfaces. Coupled with the 10-30 nm, aggregation-free morphology observed by FE-SEM and AFM, the data show that algal polysaccharides (e.g., alginates and fucoidans) act as dual-function reducing/ stabilizing agents. Compared with bacterial routes such as *Bacillus pumilus*-mediated synthesis (Mahmoud et al., 2016), the algal method offers higher particle uniformity and scalability while adhering to green-synthesis principles that favour renewable, non-toxic feedstocks (Duman et al., 2024). These bio-capped AgNPs, therefore, present a sustainable platform for downstream applications, ranging from antimicrobial coatings and antioxidant therapeutics to environmental remediation, where controlled size and surface chemistry are critical. Such applications also

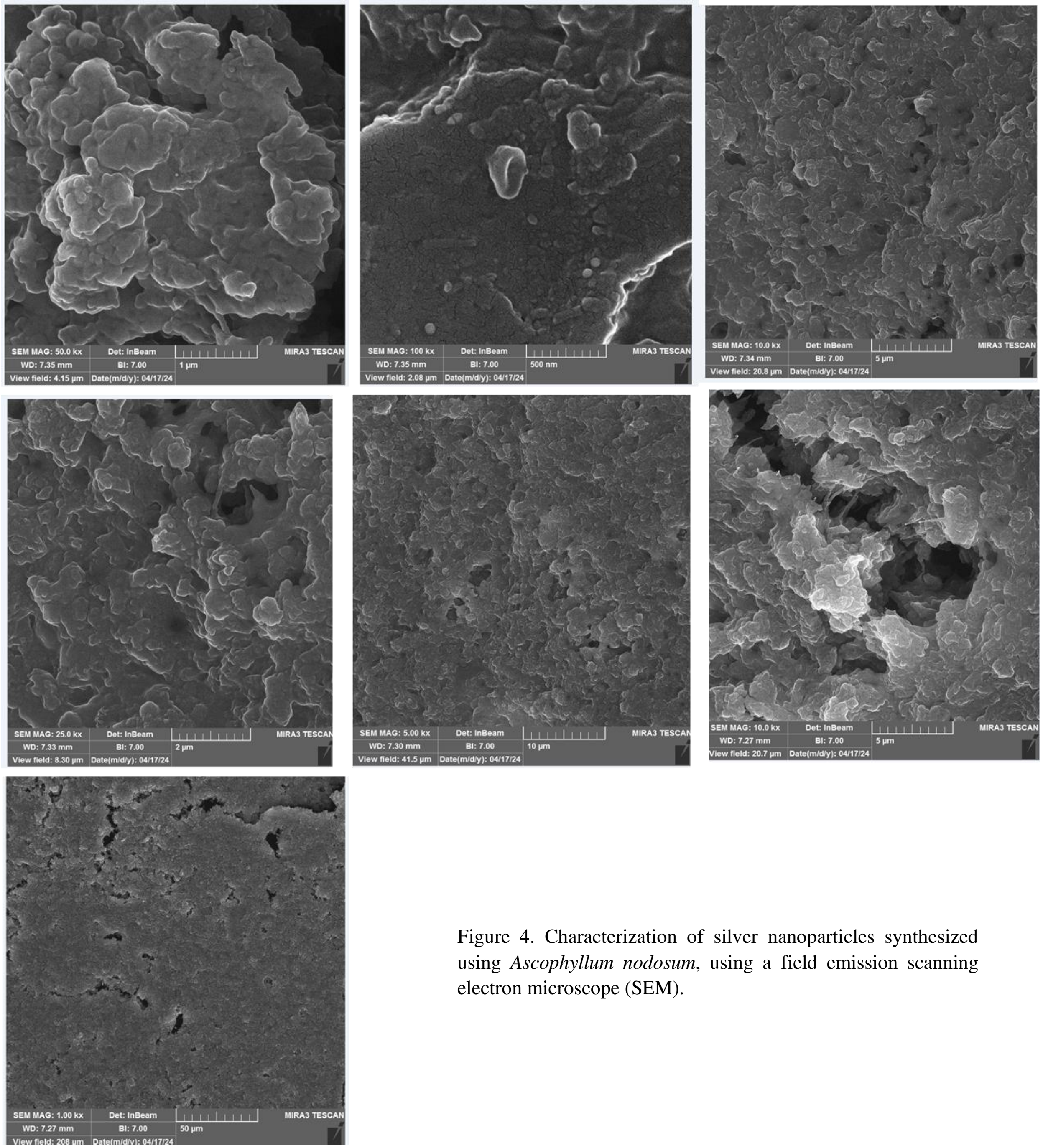

Figure 4. Characterization of silver nanoparticles synthesized using *Ascophyllum nodosum*, using a field emission scanning electron microscope (SEM).

benefit from the intrinsic antimicrobial features of nanomaterials. Notably, chitosan nanoparticles synthesized via microbial routes have demonstrated strong inhibitory activity against bacterial strains, such as *Streptococcus thermophilus*, thereby reinforcing the broader utility of biogenic nanostructures in antimicrobial therapy (Ali et al., 2022). In particular, antibacterial characterization of titanium nanoparticles nanosynthesized by *S. thermophilus* has further highlighted the versatility of microbial systems in generating potent nanostructures with biomedical potential (Aldujaili and Banoon, 2020).

Gas chromatography-mass spectrometry for *A. nodosum*: Analysis using gas chromatography-mass spectrometry (GC-MS) of chemical compounds extracted from *A. nodosum.* In Figure 6, the results are shown for a group of organic compounds on the pressure surface. In Table 1, the different compounds are identified through quantitative analysis of their quantities on the device, along with their binding

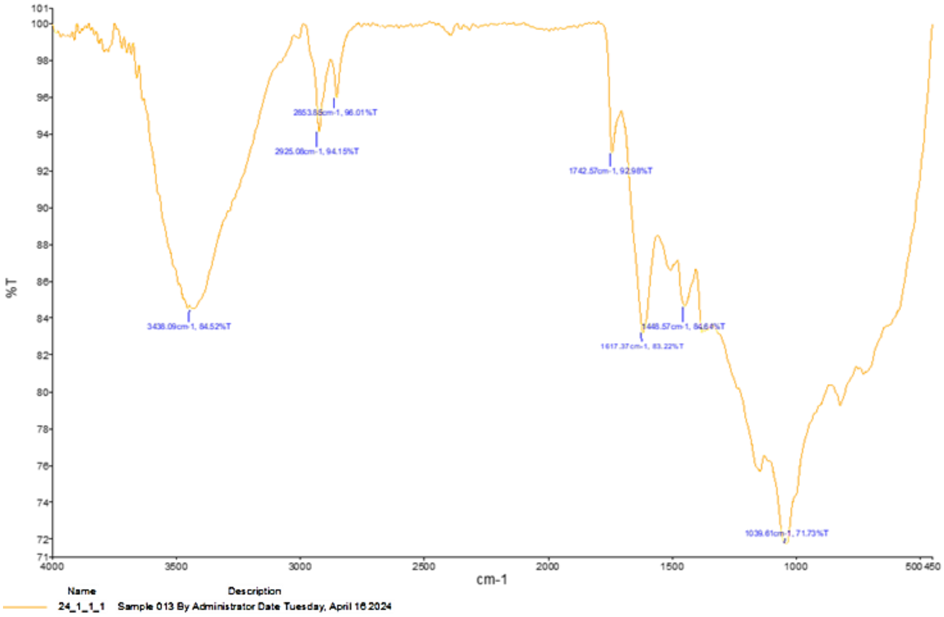

Figure 5. Infrared analysis by Fourier Transform Infrared Spectroscopy of silver nanoparticles that were synthesized using *Ascophyllum nodosum*.

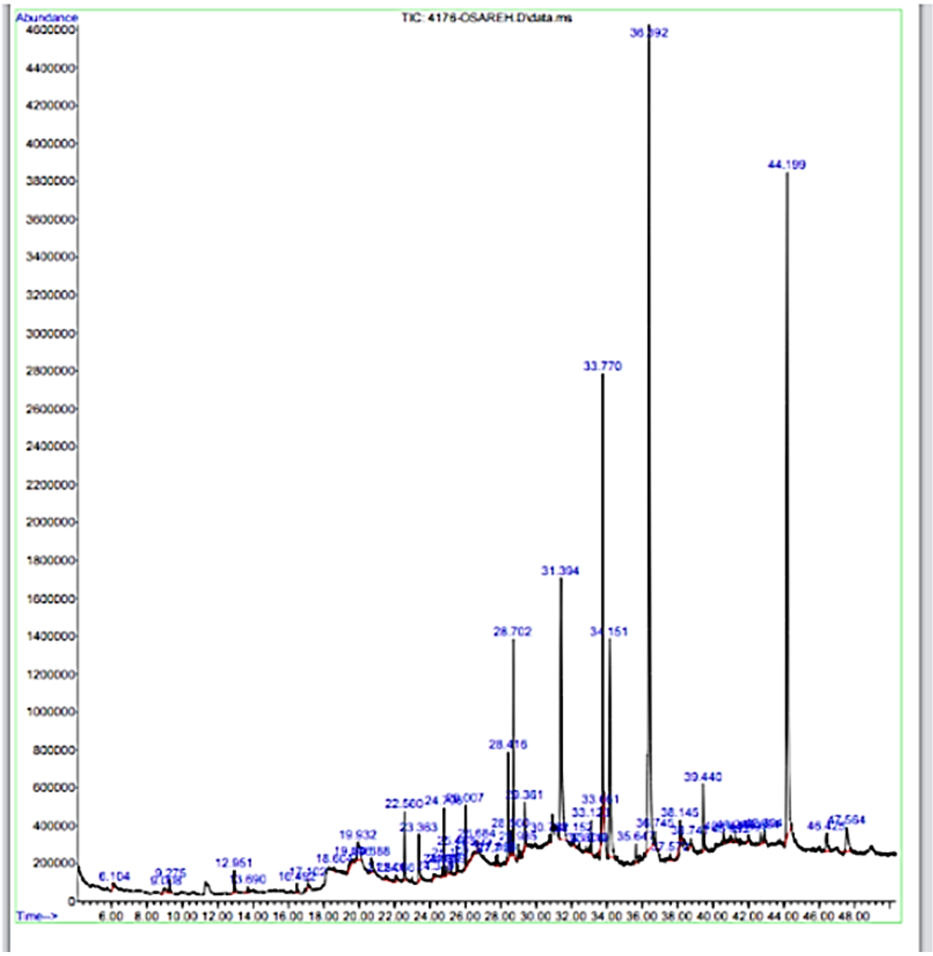

Figure 6. Gas chromatography-mass spectrometry (GC-MS) for analyzing chemical compounds of *Ascophyllum nodosum*.

times (RT) and relative distributions. For example, we note the presence of compounds such as "benzeneacetonitrile" and "tetraazatricyclo [4.4.1.1(3,8)] dodecane," which represent relatively

Table 1. Analysis of chemical compounds extracted from *Ascophyllum nodosum* using gas chromatography-mass spectrometry (GC-MS).

No	RT (min)	Area%	Name	Quality
1	6.105	0.12	Benzeneacetonitrile	46
2	9.006	0.35	Bicyclo [3.3.1] nonane	46
3	9.275	0.3	6-Methyl-1,6-heptadiene	52
4	12.949	0.5	trans-2-Decenal $$ (E)-2-Decenal	94
5	13.691	0.16	(Z)-3-azapentacyclo [5.1.0.0(2,4).0(3,5).0(6,8)] octane-7-carbonitrile	53
6	16.493	0.22	1,1,3,3-Tetramethyl-1,3-disilaphenalane	78
7	17.1	0.16	Trimethylsilyl acrylate	38
8	18.605	0.13	1,2,3-Propanetriol, 1-acetate	27
9	19.647	0.5	1,3,5-Triazine-2,4,6-triamine	38
10	19.933	1.14	Benzaldehyde, 4-fluoro-3-hydroxy-	43
11	20.69	0.66	2-(Ethylthio)phenol	49
12	21.541	0.39	1,3,6,8-Tetraazatricyclo [4.4.1.1(3,8)] dodecane	25
13	22.065	0.29	2-Methyl-3-acetyl-4,5,6,7-tetrahydrobenzo[b]furan	46
14	22.558	1.26	Methyl myristate	98
15	23.362	1.01	Tetradecanoic acid	98
16	24.317	0.22	1,2-Ethandimine, N,N'-ditrifluoroacetyl-	30
17	24.68	0.15	2-Pentadecanone, 6,10,14-trimethyl-	60
18	24.795	1.07	NEOPHYTADIENE	99
19	24.961	0.29	1-Tetradecene	27
20	25.194	0.3	citronellyl 2-methylpropanoate	46
21	25.5	0.35	3,7,11,15-Tetramethyl-2-hexadecen-1-ol	70
22	26.009	1.04	Methyl palmitate	98
23	26.476	0.21	Sorbitol	53
24	26.683	0.16	Hexadecanoic acid	41
25	27.716	0.18	Hexadecanoic acid	43
26	27.835	0.27	cis-Bicyclo [5.2.0] non-8-ene	59
27	28.416	2	2-(2,2-dimethylpropanoyl) cyclohexanone	35
28	28.561	0.34	9,12-Octadecadienoic acid (Z, Z)-, methyl ester	99
29	28.702	3.48	8-Octadecenoic acid, methyl ester	99
30	28.987	0.22	1-Octadecene	53
31	29.361	1.01	Oleic acid	99
32	30.736	0.18	Oxacyclotridecan-2-one	25
33	31.395	10.36	dimethyl docosane-1,22-dicarboxylate	35
34	32.152	0.35	9-Octadecenoic acid, (E)-	47
35	32.806	0.2	Palmitinic acid	45
36	33.019	0.15	2-Methyl-Z, Z-3,13-octadecadienol	62
37	33.122	0.59	(R)-(-)-14-Methyl-8-hexadecyn-1-ol	93
38	33.662	0.25	Bicyclo [10.1.0] tridec-1-ene	93
39	33.771	6.82	9-Octadecenal, (Z)-	94
40	34.15	7.56	Palmitin, 2-mono-	90
41	35.649	0.4	Methyl hexadecadienoate	70
42	36.391	25.6	Olein, 2-mono-	94
43	36.744	0.39	Z-9-Octadecenal	62
44	37.574	0.23	OLEIC ACID, PROPYL ESTER	49
45	38.145	0.42	9,12,15-Octadecatrien-1-ol	78
46	39.442	1.52	δ-Tocopherol	98
47	40.993	0.18	Demecolcine	35
48	41.268	0.22	Dodecahydropyrido [1,2-b] isoquinolin-6-one	38
49	41.99	0.2	9-Octadecenoic acid, (E)-	50
50	42.695	0.32	1H-Indole, 2-methyl-3-phenyl-	30
51	44.2	22.82	γ-sitosterol	95
52	46.426	0.93	Fucostenone	92

Table 2. Effect of silver nanoparticle concentrations on antioxidant activity.

Concentration (mg/mL)	**Silver**
0.12	60.15 ± 0.14^{Aa}
0.25	66.21 ± 0.18^{ABa}
0.5	$70.96\pm0.12B^{Ca}$
1	72.99 ± 0.10^{Ca}
Mean ± standard error	67.58 ± 2.85^{a}
Least significant difference (LSD) at $P<0.05$	6.24

Mean values ± standard error (SE); Different capital letters in the same column indicate significant; differences between different concentrations within the same type of nanoparticle.

low percentages, compared to other compounds such as "methyl palmitate" and "oleic acid," which had the highest percentages for each unit. The gas chromatography-mass spectrometry of Algae I, where the spectrum consists of a series of peaks appearing at different retention times, indicating the presence of multiple chemical compounds in the extract. Retention times (RT) are used to identify compounds, while the area percentage (Area%) expresses the ratio of each compound to the total components. The analysis of chemical compounds extracted from *A. nodosum* using GC-MS identified more than 50 compounds, including Benzeneacetonitrile, Bicyclo [3.3.1] nonane, trans-2-Decenal, and others, with the retention times, percentages, and quality levels of each compound reported.

The results of the GC-MS of the *A. nodosum* moss extract revealed a diverse range of biochemical compounds. This diversity of compounds indicates that *A. nodosum* contains a wide range of organic compounds, including fatty acids, phenols, and fuoxysterols, which may contribute to its multiple biological properties. In a study of Deepak et al. (2018), the antioxidant activity and inhibitory effects on α-amylase and α-glucosidase enzymes were evaluated for three solvent extracts (methanol, ethyl acetate, and hexane) derived from three marine algae species: *Sargassum wightii, Caulerpa racemosa,* and *Acanthophora spicifera*. Preliminary chemical analyses revealed the presence of diverse secondary metabolites in these extracts. Notably, the ethyl acetate extract of *S. wightii* (*S. wightii* ethyl acetate extract) exhibited potent antioxidant activity, with an IC_{50} value of 32.86 μg/mL, alongside significant inhibition of α-amylase and α-glucosidase key enzymes linked to diabetes management. GC-MS analysis of *S. wightii* ethyl acetate extract identified heptadecanoic acid as a primary bioactive compound, likely responsible for its observed bioactivities. While the present study focuses on synthesizing and characterizing silver nanoparticles from *A. nodosum*, Deepak et al. (2018) prioritized direct extraction and biochemical profiling of algal compounds. Both approaches highlight the versatility of marine algae as reservoirs of bioactive agents, with the ethyl acetate extract of *S. wightii* exemplifying their potential in therapeutic applications, such as diabetes treatment and oxidative stress mitigation (Deepak et al., 2018).

Antioxidant activity: Table 2 shows a dose-dependent increase in antioxidant activity for *A. nodosum*-synthesized silver nanoparticles (AgNPs). At 0.12 mg/mL, AgNPs exhibit 60.15±0.14% radical scavenging, rising to 72.99±0.10% at 1 mg/mL, with intermediate values of 66.21±0.18% (0.25 mg/mL) and 70.96±0.12% (0.5 mg/mL). The mean antioxidant activity across concentrations is 67.58±2.85%, reflecting consistent performance. The results of statistical analysis (LSD = 6.24, $P<0.05$) confirm significant differences between concentrations, denoted by uppercase letters (e.g., A, B, C). Lowercase letters (e.g., a) indicate no significant variation between replicates. These results highlight the concentration-responsive efficacy of AgNPs, critical for optimizing their use in antioxidant applications. Nanoparticles' biomedical efficacy can also be influenced by their surface conjugation strategies, which aim to improve delivery in drug and vaccine systems (Al-Abboodi et al., 2024).

The results also demonstrated a dose-dependent increase in antioxidant activity for *A. nodosum*-synthesized silver nanoparticles (AgNPs), rising from 60.15±0.14% at 0.12 mg/mL to 72.99±0.10% at 1 mg/mL (Table 2). This trend aligns with studies using algal-mediated synthesis, such as *Spatoglossum asperum*, where AgNPs exhibited enhanced antioxidant activity compared to raw algal extracts. These biomolecules, identified via GC-MS (Table 1), serve as capping agents, ensuring a homogeneous size distribution and colloidal stability, critical for functional performance (Xu et al., 2020).

Building on earlier work with *S. asperum*-derived AgNPs (Patel et al., 2024), our results show that the richer biochemical profile of A. nodosum produces silver nanoparticles with markedly higher antioxidant activity, reaching 72.99% radical scavenging at 1 mg mL^{-1}. Such potency positions these bio-capped AgNPs as candidates for mitigating oxidative stress disorders while adhering to green synthesis principles that favour renewable, non-toxic feedstocks (Duman et al., 2024). To probe how the bio-capped AgNPs influence cell migration and wound-healing pathways, one could adapt a microfluidic chip with an internal porous gradient. Such devices generate highly stable chemical gradients and have already been validated for precise chemotaxis assays (Al-Abboodi et al., 2011), offering a compact platform to quantify nanoparticle-guided cell responses under physiologically relevant shear conditions. Silver nanoparticles, especially when paired with beneficial soil bacteria such as *Pseudomonas fluorescens* and *Bacillus circulans*, have been shown to suppress fruit-rotting fungi (*Aspergillus niger*), thereby broadening the antimicrobial spectrum of bio-synthesized AgNPs[4]. Beyond medicine, nano-enabled remediation can dovetail with data-centric environmental tools, and machine-learning classifiers now map pollution sources in large water areas (Rashid et al., 2024; Salman et al., 2025). Coupling such bio-indicators with AgNP-based remediation would provide a rapid, ground-truth measure of air-quality gains (Fadhil et al., 2023). Together, these advances outline a closed loop where algae-based nanomaterials not only treat contaminants but also integrate with AI diagnostics, reinforcing *A. nodosum* as a sustainable platform for next-generation eco-friendly nanotechnologies. This sustainable paradigm aligns with parallel efforts in wastewater treatment, where the valorization of diatomaceous earth as a sustainable eco-coagulant has demonstrated promising pollutant removal efficiency through optimization using response surface methodology (Benouis et al., 2022).

Conclusion

This work confirms that water extracts of the brown alga *A. nodosum* can bio-reduce Ag^+ ions into uniformly spherical silver nanoparticles (~10-30 nm). Spectroscopic and microscopic analyses verify high elemental purity and stable bio-capping, while DPPH assays demonstrate a concentration-dependent radical-scavenging efficiency that peaks at 72.99%. These traits position the algal AgNPs as promising ingredients for topical antioxidant products and other eco-friendly nanotechnologies in health care, cosmetics, and surface-coating industries.

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