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RESEARCH ARTICLE

GC-MS-based phytochemical profiling and anti-diabetic efficacy of *Sargassum tenerrimum*-mediated silver nanoparticles

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Abstract

Marine macroalgae, particularly *Sargassum tenerrimum*, have emerged as a significant source of bioactive compounds with potential therapeutic applications. Study focuses on the synthesis, characterization and antidiabetic activity of silver nanoparticles (AgNPs) derived from *S. tenerrimum* chloroform extract. GC-MS analysis revealed diverse bioactives, including fatty acids such as hexadecanoic acid, oleic acid unsaturated compounds like α-linolenic acid and linoleic acid. These compounds enhance insulin sensitivity, regulate lipid metabolism and support β-cell functionality. Additionally, ethyl isoallocholate and glycine derivatives contribute to insulin synthesis and glucose homeostasis through molecular pathways. AgNPs were synthesized via an eco-friendly approach, confirmed by UV-Vis spectroscopy, FT-IR analysis (hydroxyl and carbonyl functional groups for reduction and stabilization) and SEM imaging (spherical nanoparticles with nanoscale diameters). Glucose utilization assays conducted on L6 skeletal muscle cells demonstrated significant, dose-dependent activity, with 91.26 % glucose uptake. Work highlights the dual role of *S. tenerrimum* bioactives in glucose metabolism modulation and nanoparticle stabilization, emphasizing their therapeutic synergy. The findings establish *S. tenerrimum*-derived AgNPs as promising, sustainable agents for managing diabetes, warranting further molecular and pharmacological investigations for broader biomedical applications.

Keywords: antidiabetic activity; FT IR; GC-MS analysis; glucose metabolism; phytochemicals; *Sargassum tenerrimum*; SEM; silver nanoparticles

Introduction

Marine environments harbour an extensive diversity of algal seaweeds, with over 10000 species reported globally (1). These plant-like macroscopic organisms, lacking true stems, roots and leaves, are classified into three groups: green algae (Chlorophyta), red algae (Rhodophyta) and brown algae (Phaeophyta). Among these, the genus *Sargassum*, a prominent group of brown macroalgae within the class Phaeophyceae, is widely distributed across temperate and tropical oceans. Its species have been documented in diverse locations, including the *Tho Chu Archipelago* (2), *Cham Islands* (3) and the coasts of Algeria (4). In India, *Sargassum* is abundant along coastal regions, such as the southern coastline (5), the Gulf of Kutch (6) and Tamil Nadu's southern districts in India (7).

Sargassum tenerrimum, has gained attention for its unique bioactive properties. It contains polysaccharides like alginic acid, with a molecular mass of 26 ± 5 kDa and fucoidan, with a molecular mass of 30 ± 5 kDa. These compounds contribute to its reported antiviral activity (8). The species has also been investigated for its potential to inhibit oxidative stress through sulphated polysaccharides, which scavenged intracellular reactive oxygen species (9). Furthermore, ethanol extracts demonstrated anti-allergic properties *in vivo* (10), while chromatographic fractions exhibited insecticidal efficacy by reducing DNA and protein content in *Dysdercus cingulatus* (7).

The phytochemical profile of *S. tenerrimum* reveals a wealth of metabolites, including steroids, phenolic groups, flavonoids, saponins, tannins, terpenoids and reducing sugars (11). These metabolites have been linked to antibacterial (12), antidiabetic (13), antioxidant, antitumor (14) and antiviral activities (8). Notably, the crude extract of *S. tenerrimum* exhibited significant anti-plasmodial activity, with Ag-ST nanoparticles showing IC_{50} values of 7.71 ± 0.39 µg/mL and 23.93 ± 2.27 µg/mL against *Plasmodium falciparum* and *Plasmodium berghei*, respectively (15).

The synthesis of silver nanoparticles (AgNPs) using natural precursors like *S. tenerrimum* has become a focus of research due to their unique optical, electronic and biological properties. These nanoparticles are characterized by phytochemical screening, UV-visible spectroscopy and structural elucidation using techniques like scanning electron microscopy (SEM) and GC-MS. *In vitro* studies have highlighted their significant antidiabetic potential, suggesting their role in therapeutic applications. The present study aims to investigate

the phytochemical constituents, spectral characteristics and in vitro antidiabetic activity of AgNPs synthesized from *S. tenerrimum*, underscoring the species' potential in biomedical and environmental applications.

Materials and Methods

Sample collection and preparation

S. tenerrimum sample was collected in December 2022 from Murud-Janjira, Raigad District, Maharashtra, India (18°19′36′′N and 72°57′19′′E). The seaweed was thoroughly cleaned with seawater to remove sand, debris and epiphytes, then shade-dried for 7-8 days. The sample were powdered and stored in airtight containers, with a portion submitted for taxonomic identification. The powdered samples were refrigerated for further analysis (16).

Extraction of bioactive compounds

A 50 g powdered sample was extracted using HPLC-grade chloroform by cold extraction, maintained in a dark room for 36 hr with continuous shaking. The extract was filtered through Whatman No. 1 paper and the solvent was evaporated using a rotary evaporator. The residue was stored at 4 °C. GC-MS characterization was performed to identify volatile bioactive compounds (17).

Synthesis of silver nanoparticles (AgNPs)

AgNPs were synthesized by adding 5 mL of *S. tenerrimum* chloroform extract to 1 mL of 1M aqueous silver nitrate ($AgNO_3$) solution at room temperature. The reaction mixture was stirred for 10 min on a rotary shaker, with colour change indicating the reduction of Ag+ ions (18-20).

Characterization of silver nanoparticles

The characterization of silver nanoparticles (AgNPs) synthesized from *S. tenerrimum* extract involved UV-Vis spectroscopy, FT-IR spectroscopy and SEM analysis. UV-Vis spectrophotometry confirmed nanoparticle synthesis through a colour change from green to yellowish-brown, with a stable surface plasmon resonance peak at 417 nm. FT-IR analysis identified functional groups such as hydroxyl, carbonyl and amine groups responsible for reducing and stabilizing AgNPs, highlighting the eco-friendly nature of the process (20-22). SEM imaging revealed uniformly spherical nanoparticles with sizes ranging from a few nanometres to tens of nanometres, prepared on a carbon-coated copper grid without requiring additional coatings due to silver's conductive nature. This comprehensive analysis validated the formation, stability and morphology of the AgNPs, ensuring their potential for biological applications (18, 23, 24).

Cell line culturing and maintenance

L6 rat skeletal muscle cells were cultured in RPMI-1640 medium with 10 % fetal calf serum under 5 % CO_2 at 37 °C. After 90 % confluence, the cells were subculture by trypsinization and maintained with fresh media for experiments (25).

Glucose utilization assay

L6 cells were seeded at 5000 cells/well in 96-well plates, differentiated in DMEM with 2 % FBS for five days and treated with AgNPs at concentrations of 100 and 200 µL/well. Insulin (0.04 IU/10 µL/well) served as the positive control. After 48 hr, cells were exposed to 8 mM glucose solution and absorbance was measured at 510 nm using a UV spectrophotometer. Glucose utilization was calculated as the difference between glucose left in the medium and the initial glucose concentration, expressed as a percentage of untreated controls (26).

To elucidate the molecular mechanism underlying the observed increase in glucose utilization, we further hypothesize that the AgNPs may enhance glucose uptake via stimulation of insulin signalling pathways. Based on previous literature and related nanoparticle studies, such enhancement is often mediated by activation of the PI3K/Akt pathway, leading to GLUT4 translocation to the cell membrane (Fig. 1). Additionally, AgNPs may mimic insulin-like effects or modulate AMP-activated protein kinase (AMPK) activity, a key regulator of glucose homeostasis under cellular energy stress (27). Although the current study primarily focused on functional glucose uptake assays, pathway validation can be pursued in future studies using Western blotting or qPCR to detect expression and phosphorylation levels of Akt, IRS-1, GLUT4 and AMPK in treated cells.

Statistical analysis

Data were analysed using Graph Pad Prism software, with results expressed as mean ± standard deviation. Statistical significance was determined via one-way ANOVA ($p < 0.05$).

Results and Discussion

The GC-MS analysis of the chloroform extract of *S. tenerrimum* has revealed a diverse array of bioactive compounds (Fig. 2), including sterols, fatty acids, oleochemicals and non-fatty acid derivatives. These compounds demonstrate significant pharmacological and industrial potential due to their structural diversity and associated bioactivities. A rich chemical profile dominated by fatty acids and derivatives, confirming its suitability for applications such as nanoparticle synthesis and therapeutic uses.

Among saturated fatty acids, hexadecanoic acid (palmitic acid) was the most abundant (48.13 %), followed by octadecanoic acid (13.80 %). These compounds are known for their stability and bioactivity, including antimicrobial and antioxidant properties (Table 1). The unsaturated fatty acids include (Z,Z,Z)-9,12,15-octadecatrienoic acid (14.79 %) and (Z,Z)-9,12-octadecadienoic acid (10.61 %), both of which contribute to potential anti-inflammatory and hypolipidemic effects. These compounds enhance the functional properties of the synthesized nanoparticles (Table 2). Non-fatty acid compounds like 1-octadecene and 6,10,14-trimethyl-2-pentadecanone were also identified, albeit in smaller concentrations. These compounds may act as reducing agents or stabilizers in the synthesis process (Table 3).

One of the key steroidal compounds identified is ethyl isoallocholate ($C_{26}H_{44}O_5$), detected at a retention time (RT) of 10.30. This compound is classified as a sterol and is known for its multifunctional therapeutic properties. Ethyl isoallocholate has been reported to possess antibacterial and antioxidant activities, which make it a promising candidate for pharmaceutical formulations. Additionally, it demonstrates anti-tumor and cancer-preventive properties, along with applications as a pesticide and chemo-preventive agent. Its versatility highlights

Table 1. GC-MS analysis of the chloroform extract with saturated fatty acids and their derivatives

PK	RT (min)	Name	Conc. (%)	Similarity (%)	Base peak (m/z)	Molecular formula	Molecular weight (g/mol)
1	7.38	Tetradecanoic acid	2.47	98	74	$C_{14}H2_8O_2$	228.37
3	8.57	12-Methyl tetradecanoic acid	0.22	93	74	$C_{15}H_{30}O_2$	242.40
5	8.91	Pentadecanoic acid	1.03	97	74	$C_{15}H_{30}O_2$	242.40
7	9.61	5,9,13-Trimethyl tetradecanoic acid	0.96	58	74	$C_{17}H_{34}O_2$	270.45
8	9.84	Tridecanoic acid	0.18	98	74	$C_{13}H_{26}O_2$	214.35
10	10.07	Hexadecanoic acid	48.13	99	74	$C_{16}H_{32}O_2$	256.42
12	11.73	2-Methyl-octadecanoic acid	0.94	93	88	$C_{19}H_{38}O_2$	298.51
14	12.09	Heptadecanoic acid	2.47	98	74	$C_{17}H_{34}O_2$	270.45
21	13.72	Octadecanoic acid	13.80	99	74	$C_{18}H_{36}O_2$	284.48

Table 2. GC-MS analysis of the chloroform extract with unsaturated fatty acids and their derivatives

PK	RT (min)	Name	Conc. (%)	Similarity (%)	Base peak (m/z)	Molecular formula	Molecular weight (g/mol)
4	8.75	(E)-9-Dodecenoic acid	0.31	52	55	$C_{12}H_{22}O_2$	198.30
19	13.13	(Z,Z)-9,12-Octadecadienoic acid	10.61	99	67	$C_{18}H_{32}O_2$	280.46
20	13.32	(Z,Z,Z)-9,12,15-Octadecatrienoic acid	14.79	98	79	$C_{18}H_{30}O_2$	278.44

Table 3. GC-MS analysis of the chloroform extract with non-fatty acid compounds

PK	RT (min)	Name	Conc. (%)	Similarity (%)	Base peak (m/z)	Molecular formula	Molecular weight (g/mol)
2	8.30	1-Octadecene	0.55	98	57.83	$C_{18}H_{36}$	252.48
6	9.27	6,10,14-Trimethyl-2-pentadecanone	1.94	98	43	$C_{18}H_{36}O$	268.48
11	11.46	(E)-15-Heptadecenal	0.36	98	41.55	$C_{17}H_{32}O$	252.44
15	12.30	1,2,2,6,8-Pentamethyl-7-oxabicyclo[4.3.1]dec-8-en-10-one	0.19	25	43	$C_{15}H_{22}O_2$	234.34
16	12.61	Hexadecane-1,2-diol	0.23	60	43.55	$C_{16}H_{34}O_2$	258.44
17	12.92	n-Heneicosane	0.29	96	43.57	$C_{21}H_{44}$	296.58
18	13.02	Eicosan-3-ol	0.18	35	57	$C_{20}H_{42}O$	298.56

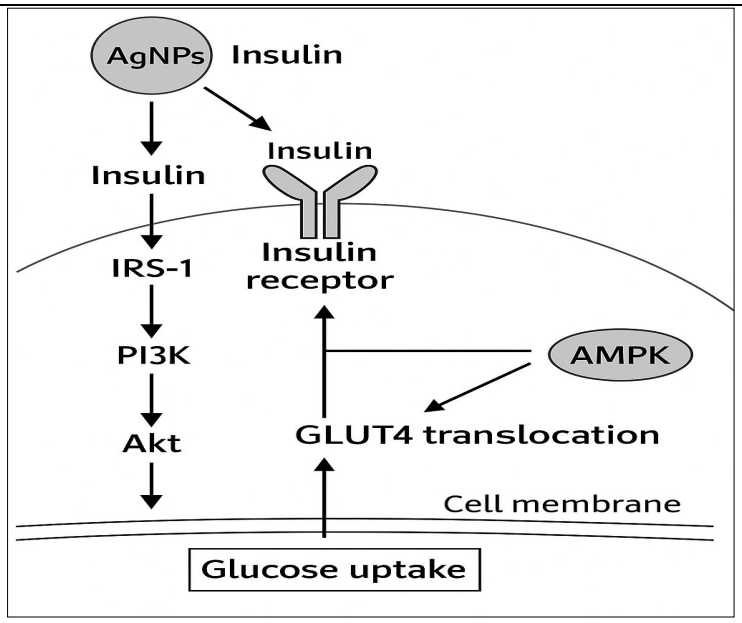

Fig. 1. Molecular mechanisms of glucose uptake.

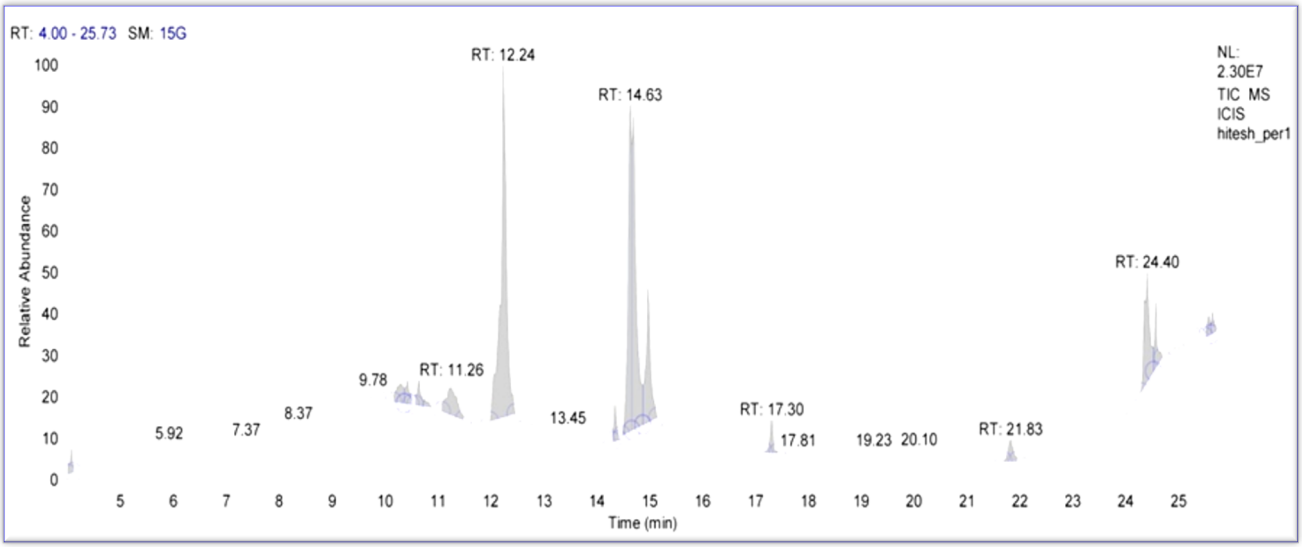

Fig. 2. Chloroform extract of *Sargassum tenerrimum* by GC MS.

its potential use in diverse therapeutic and environmental applications (28).

Among the fatty acids, cis-13-eicosenoic acid ($C_{20}H_{38}O_2$), identified at RT 24.40, is a noteworthy oleochemical. This compound is widely used in pharmaceuticals, cosmetics and food products due to its stability and bioavailability. Similarly, octadecenoic acid ($C_{18}H_{36}O_2$), detected at RT 14.97, is associated with a broad spectrum of bioactivities. It exhibits anti-inflammatory, antiandrogenic and hypocholesterolemic properties, along with its roles as a dermatitigenic agent, insect repellent and flavoring compound (Table 4). These bioactivities render it suitable for applications in both medical and commercial industries (29, 30).

Additionally, oleic acid ($C_{18}H_{34}O_2$), identified at RT 14.63, has been widely studied for its antibacterial bioactivity. This compound plays a crucial role in combating bacterial infections, which further supports its use in antimicrobial product development (17).

The chloroform extract also contains non-fatty acid compounds like ethylbenzene (C_8H_{10}), which was identified at RT 4.07. Ethylbenzene is widely utilized as a solvent in the manufacturing of insecticides, paints, adhesives and rust preventives. Additionally, it serves as an antiknock agent in aviation and motor fuels, reflecting its significance in industrial applications (31, 32).

The unsaturated fatty acid *trans-13-octadecenoic acid* is another prominent compound in the extract. Known for its anti-inflammatory, antiandrogenic and insecticidal properties, it has potential applications in treating inflammatory conditions and as a pesticide. The compound also exhibits dermatitigenic properties, which may influence its role in dermatological products (17, 33).

The chloroform extract of *S. tenerrimum* demonstrates a rich chemical composition with significant pharmacological and industrial potential. Compounds like *ethyl isoallocholate*, *oleic acid* and *cis-13-eicosenoic acid* contribute to the extract's antimicrobial, anti-inflammatory and antioxidant properties, making it suitable for applications in pharmaceuticals, nutraceuticals and cosmetics. The presence of industrially relevant compounds such as ethylbenzene and octadecenoic acid further emphasizes the extract's versatility, underscoring the importance of *S. tenerrimum* as a sustainable bioresource for various scientific and industrial applications.

Characterization and effectiveness of silver nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) synthesized from the *S. tenerrimum* chloroform extract were comprehensively characterized to confirm their successful synthesis, stability and morphology.

UV-Vis spectroscopy

The formation of AgNPs was confirmed by the appearance of a stable surface plasmon resonance (SPR) peak at 250 nm, a characteristic wavelength for silver nanoparticles. This peak indicates the collective oscillation of conduction electrons due to photon interaction, confirming the reduction of silver ions to silver nanoparticles. The peak stability over several days further validated the chemical stability of the synthesized nanoparticles and their resistance to aggregation under experimental conditions (Fig. 3).

FT-IR analysis

Fourier-transform infrared (FT-IR) spectroscopy was used to identify the functional groups present in the *S. tenerrimum* extract, which contributed to reducing and stabilizing the nanoparticles. The analysis revealed peaks corresponding to hydroxyl (O-H), carbonyl (C=O) and amine (N-H) groups. These functional groups likely played a dual role by reducing silver ions to elemental silver and capping the nanoparticles, preventing

Table 4. Compounds identified in chloroform extract of S. *tenerrimum* by GC MS analysis

Sr. No	RT (min)	Name of compound	Molecular formula	Molecular weight (g/mol)	Reference
1	4.07	Ethylbenzene	C_8H_{10}	106.17	(31-33)
2	10.30	Ethyl isoallocholate	$C_{26}H_{44}O_5$	436.63	(28, 32, 34, 35)
3	10.30	5,6,7,8,9,10-Hexahydro-9-methyl-spiro[2H-1,3-benzoxazine-4,1′-cyclohexane]-2-thione	$C_{14}H_{23}NOS$	253.4	(36)
4	10.30	Tetradecanoic acid	$C_{14}H_{28}O_2$	228.38	(37)
5	10.30	Hexadecanoic acid, 1-(hydroxymethyl)-1,2-ethanediyl ester	$C_{35}H_{68}O_5$	568.92	(16, 37)
6	10.43	Vitamin A palmitate	$C_{36}H_{60}O_2$	524.87	(38)
7	10.43	Tetraacetyldxylonic nitrile	$C_{14}H_{17}NO_9$	343.29	(35)
8	10.43	Hexadecanoic acid, (2-phenyl-1,3-dioxolan-4-yl)methyl ester, cis	$C_{26}H_{42}O_4$	418.62	(16, 38)
9	10.64	Glycine, N-[24-Oxo-3α,12α-bis(trimethylsiloxy)-5β-cholan-24-yl] glycine methyl ester	$C_{36}H_{69}NO_6Si_3$	696.2	(39)
10	10.64	Cholan-24-oic acid, 3,12-dihydroxy-, 2,5-dioxo-1-pyrrolidinyl ester, (3α,5β,12α)-	$C_{28}H_{43}NO_6$	489.65	(40)
11	10.64	9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl)methyl ester, cis	$C_{28}H_{44}O_4$	444.66	(41)
12	10.64	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[(trimethylsilyl)oxy]methyl] ethyl ester, (Z,Z,Z)-	$C_{27}H_{52}O_4Si_2$	496.88	(41)
13	11.26	Octadecanoic acid, (2-phenyl-1,3-dioxolan-4-yl) methyl ester, cis	$C_{28}H_{46}O_4$	446.67	(41)
14	12.24	n-Hexadecanoic acid	$C_{16}H_{32}O_2$	256.43	(16)
15	12.24	Pentadecanoic acid	$C_{15}H_{30}O_2$	242.4	(37)
16	12.24	Tridecanoic acid	$C_{13}H_{26}O_2$	214.35	(37)
17	14.35	Heptasiloxane, hexadecamethyl	$C_{16}H_{48}O_6Si_7$	533.15	(43)
18	14.63	Oleic acid	$C_{18}H_{34}O_2$	282.47	(18, 20, 39)
19	14.97	Octadecanoic acid	$C_{18}H_{36}O_2$	284.48	(18, 20, 39)
20	17.30	Cyclononasiloxane, octadecamethyl	$C_{18}H_{54}O_9Si_9$	667.39	(44)
21	21.83	Cyclodecasiloxane, eicosamethyl	$C_{20}H_{60}O_{10}Si_{10}$	741.54	(44)
22	24.40	Octadecenoic acid	$C_{19}H_{36}O_2$	296.49	(17, 30)
23	24.40	cis-13-Eicosenoic acid	$C_{20}H_{38}O_2$	310.52	(28, 32)
24	24.57	Heptasiloxane, hexadecamethyl	$C_{16}H_{48}O_6Si_7$	533.15	(44)
25	25.57	Oleic acid, 3-(octadecyloxy)propyl ester	$C_{39}H_{76}O_3$	593.03	(45)
26	25.64	Spirost-8-en-11-one, 3-hydroxy-	$C_{27}H_{40}O_4$	428.61	(46)

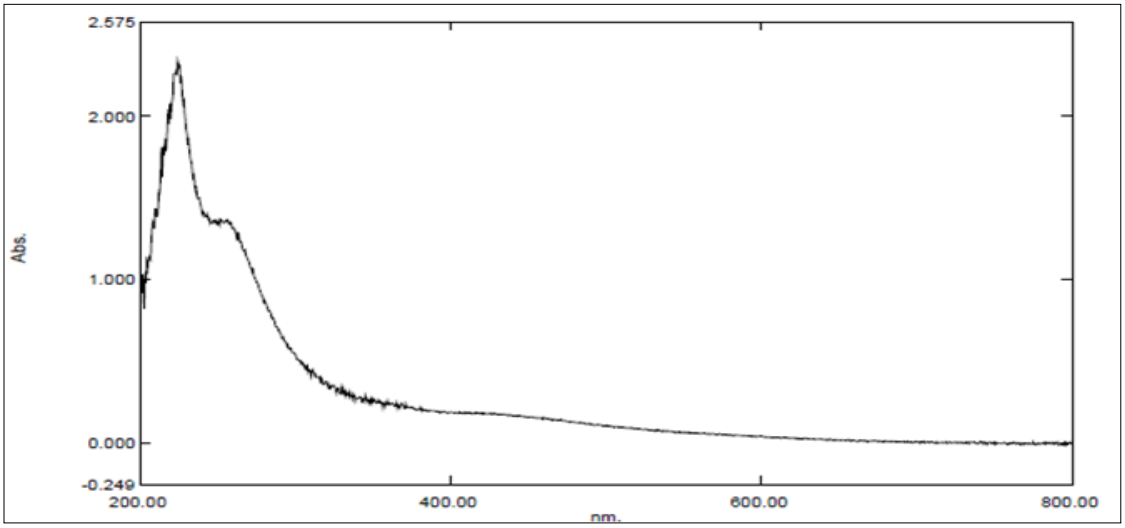

Fig. 3. UV Spectrum peak report of nanoparticle of *S. tenerrimum*.

their agglomeration. The eco-friendly synthesis mechanism highlighted the significance of the phytochemical-rich extract in forming bioactive nanoparticles (Fig. 4).

Scanning electron microscopy (SEM)

The morphological properties of the AgNPs were analysed using SEM. The images showed uniformly distributed, spherical nanoparticles with diameters ranging from a few nanometers to tens of nanometers. The high resolution of SEM imaging provided insights into the nanoparticle size distribution and surface characteristics. The absence of additional coatings on the particles was attributed to the natural conductivity of silver, making the particles suitable for various biomedical applications (Fig. 5).

Antidiabetic activity of AgNPs

The hypoglycemic potential of AgNPs synthesized from *S. tenerrimum* extract was evaluated through a glucose utilization assay using L6 rat skeletal muscle cells (Table 5). The assay demonstrated a significant, dose-dependent enhancement of glucose uptake in cells treated with AgNPs. At a concentration of 20 µg/mL, AgNPs achieved a glucose utilization rate of 91.26 %, which significantly exceeded the rate observed with insulin-treated cells (77.59 %) ($p < 0.001$). This indicates that the AgNPs effectively mimic or enhance insulin's action in promoting glucose uptake. At 10 µg/mL, the AgNPs also displayed considerable activity (79.17 %), highlighting their effectiveness even at lower concentrations. The results suggest that the synthesized AgNPs contain bioactive compounds capable of modulating glucose metabolism. The presence of functional phytochemical groups identified during FT-IR characterization is contribute to this activity by facilitating glucose transport and cellular metabolism (26, 47). Additionally, the nanoparticles' small size and high surface area are likely to enhance their bioavailability and interaction with cellular targets (48).

These findings demonstrate the potential of *S. tenerrimum* derived AgNPs as a natural, eco-friendly therapeutic for managing diabetes mellitus. The study further underscores the importance of marine-derived resources in developing novel pharmacological agents.

Table 5. Effect of aqueous extract and nanoparticles of S. *tenerrimum* on glucose utilization in L6 cell line

Sr. No	Group	Dose	% of Glucose utilization
01	Insulin	0.04 IU/10 µL	77.59 ± 0.201
02	*S. tenerrimum* nanoparticles	10 µg/mL	79.17 ± 0.178
03	*S. tenerrimum* nanoparticles	20 µg/mL	91.26 ± 0.210
	$P < 0.001$ = ***		

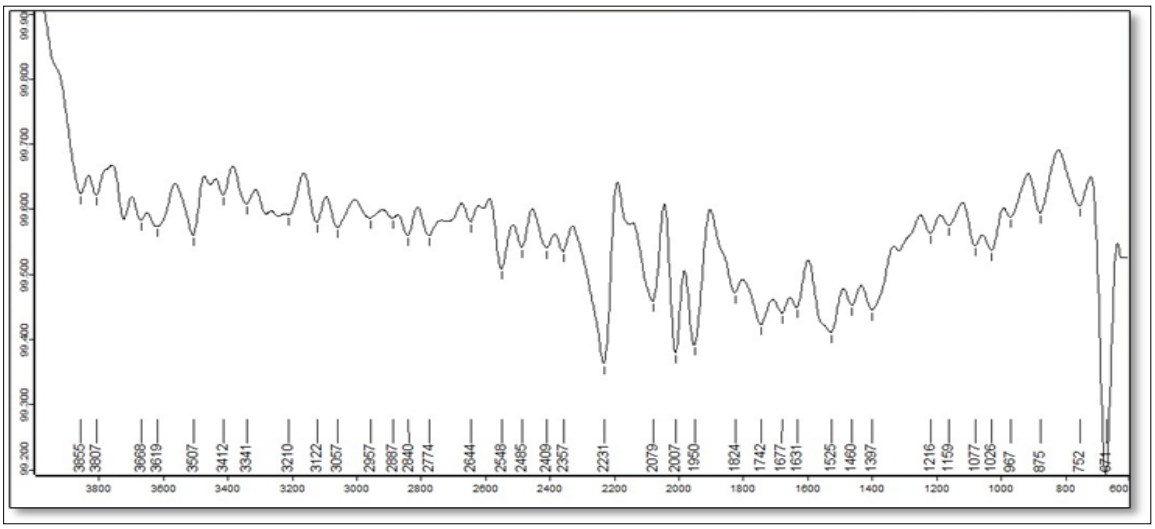

Fig. 4. IR spectral report of nanoparticle of *S. tenerrimum*.

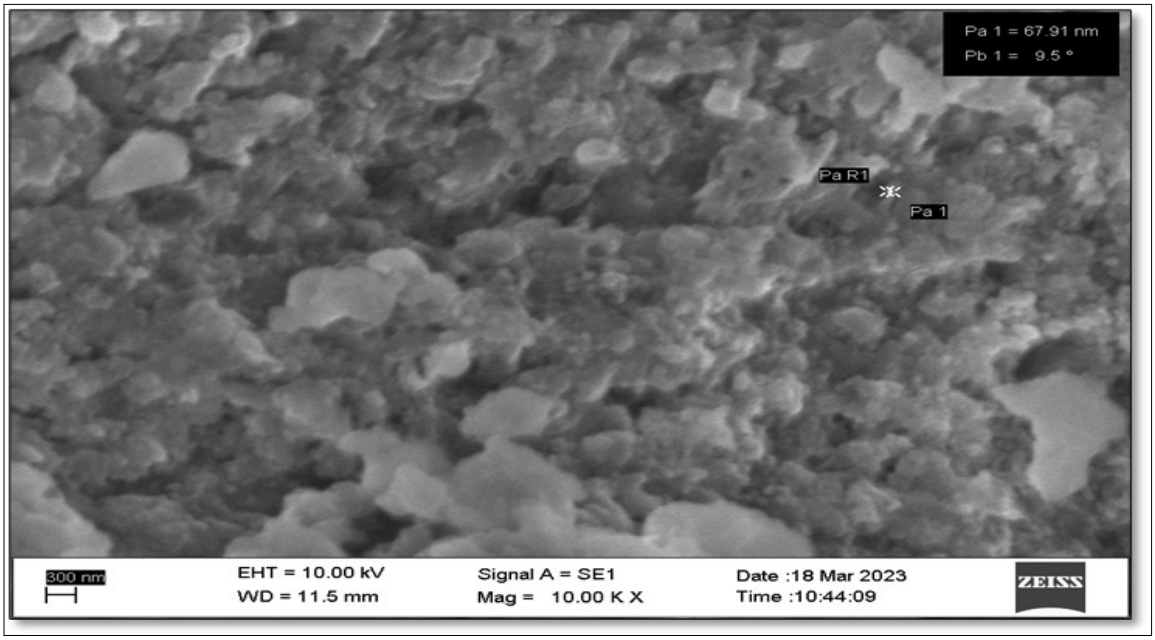

Fig. 5. Nanoparticles derived from extract of *S. tenerrimum*.

Conclusion

The study demonstrates the significant antidiabetic potential of silver nanoparticles (AgNPs) synthesized from the chloroform extract of *S. tenerrimum*. Glucose utilization assays showed a dose-dependent enhancement in glucose uptake in L6 skeletal muscle cells, with 91.26 % utilization at 20 µg/mL, surpassing the 77.59 % of insulin-treated controls. This confirms the efficacy of AgNPs in modulating glucose metabolism.

The phytochemical composition of *S. tenerrimum*, identified through GC-MS analysis, provided critical insights into compounds directly or indirectly involved in insulin synthesis and glucose regulation. The key compounds have been identified as directly or indirectly involved in insulin synthesis and glucose metabolism based on their bioactivities reported in current work are hexadecanoic acid (palmitic acid) (RT 10.07) plays a role in the regulation of insulin secretion by pancreatic β-cells. It acts as an energy source and modulates insulin signaling pathways. Excessive amounts, however, can induce insulin resistance (49, 50). Oleic acid (RT 14.63) enhances glucose uptake and insulin sensitivity in skeletal muscle cells. It is also involved in the regulation of lipid metabolism, making it significant in combating metabolic syndromes such as diabetes (51). (Z,Z,Z)-9,12,15-octadecatrienoic acid (α-linolenic acid) (RT 13.32) has anti-inflammatory effects and improves insulin sensitivity. It promotes glucose uptake by activating pathway such as AMPK, which is crucial for glucose metabolism (52). (Z,Z)-9,12-octadecadienoic acid (linoleic acid) (RT 13.13) is involved in enhancing insulin action by modulating the composition of membrane phospholipids, thereby affecting insulin receptor function (53). Ethyl isoallocholate (EIA) (RT 10.30) is indirectly influence insulin-glucose metabolism by acting as a bile acid receptor agonist, primarily through the Farnesoid X Receptor (FXR), which then modulates gene expression involved in glucose uptake, gluconeogenesis and lipid metabolism, thereby impacting overall insulin sensitivity and blood glucose levels (54). Glycine, N-[24-Oxo-3α, 12α-bis(trimethylsiloxy)-5β-cholan-24-yl] glycine methyl ester (RT 10.64) is a critical compound in metabolic pathways, including insulin secretion. It helps maintain glucose homeostasis and supports β-cell health (55).

The correlation between the phytochemical composition and the functional properties of AgNPs highlights their dual role: modulating glucose metabolism and serving as reducing and stabilizing agents in nanoparticle synthesis. These findings establish *S. tenerrimum*-derived AgNPs as promising eco-friendly agents for managing diabetes mellitus. Their bioactive composition and synergistic action in nanoparticle synthesis and glucose regulation provide a sustainable approach for therapeutic applications and warrant further exploration of their mechanisms in metabolic disease management.

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Authors' contributions

AK, RB and JK conceptualized and designed the study. RB and AK performed the experiments, including nanoparticle synthesis and GC-MS analysis. MC and NM contributed to the testing and biological activity evaluation, including the glucose utilization assay. AS supervised the research and provided critical insights for data interpretation and manuscript preparation. All authors reviewed, revised and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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