Rapid synthesis of gold nanoparticles from some Egyptian seaweed: Characterization and antidiabetic potential

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ABSTRACT: Diabetes mellitus (DM), or Type 2 diabetes comprises a chronic metabolic condition defined by increased blood glucose levels. presenting substantial global health challenges. Nanomaterials, specifically gold nanoparticles 'AuNPs', are increasingly being investigated for possessing unique properties and biocompatibility in biomedical potential uses. This study explores the rapid and ecofriendly biosynthesis of 'AuNPs' using aqueous extracts from five Egyptian seaweeds: *Ulva linza*, *Ulva fasciata*, *Ulva intestinalis*, *Petalonia fascia*, and *Corallina officinalis*. Gold nanoparticles were efficiently synthesized by heating each seaweed extract at 90℃ for 10 min, with *Petalonia fascia* (O.F.Müller) Kuntze demonstrating superior efficacy evidenced by a distinct purple color and a surface plasmon resonance peak at 540 nm. Characterization using UV-vis spectroscopy, transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FT-IR), and X-ray diffraction (XRD) confirmed the synthesis of spherical 'AuNPs' with an average diameter of 9.02 ±1.7 nm and crystalline nature. In vitro assays revealed significant inhibition of α-amylase and α-glucosidase enzymes by the 'AuNPs', with IC50 values, surpassing the positive control, acarbose. These results highlight the potent antidiabetic properties of 'AuNPs' synthesized using *Petalonia fascia* extract, suggesting their potential as natural and effective therapeutic agents for managing DM.

Keywords: antidiabetic effect, diabetes management, gold nanoparticles, green synthesis, *Petalonia fascia*

INTRODUCTION

Diabetes mellitus, also known as DM, is a lifelong metabolic disorder characterized by excessive blood glucose levels caused by inadequate insulin synthesis, inadequate insulin action, or both, which leads to a high death rate globally. The increasing prevalence of diabetes worldwide and its related risks highlight the need for novel therapeutic approaches.

In recent years, Nanomaterial(s) have shown immense potential in the field of nanomedicine, given their unique physicochemical properties, biocompatibility, and surface functionalization (Zhao and Castranova 2011). Of the different inorganic nanoparticles, gold nanoparticles 'AuNPs' have been extensively explored for their different biomedical applications. This is due to its stability, easy to synthesize, size-controlled synthesis and low- toxicity profile (Chen *et al*., 2021; Aziz *et al*., 2022). Of the approximately two thousand seaweed species that make up marine resources, only a small number have been linked to the generation of nanoparticles (Jaison *et al*., 2024).

The implication of 'AuNPs' in many nanomedicine applications is a very promising route because of their numerous benefits such as non-immunogenicity, biocompatibility, and no cytotoxicity in human cells (Spivak *et al*., 2013; Connor and Broome 2018).

One of the most recent findings in the nanomedicine field is discovering the anti-diabetic potential of gold nanoparticles (BarathManiKanth *et al*., 2010). Earlier studies on 'AuNPs' have demonstrated encouraging findings in this area, including reducing blood glucose and having a protective effect against problems related to diabetes (Manna *et al*., 2019; Alomari *et al*., 2020; Al-Shwaheen *et al*., 2022). Numerous investigations have validated the anti-diabetic potential of gold nanoparticles, which are biosynthesized using extracts from various plant sources (Kumar *et al*., 2011; Daisy and Saipriya 2012; Ansari *et al*., 2019; Ponnanikajamideen *et al*; 2019).

Biosynthesis of gold nanoparticles was demonstrated using many organisms such as bacteria, fungi, plant extracts, and macro & micro-algae to mediate the synthesis of gold nanoparticles (Kharissova *et al*., 2013). Seaweeds possess many bioactive compounds such as lipids, proteins, carotenoids, carbohydrates, vitamins and many other bioactive secondary metabolites which have the potential to function as an efficient reducing, capping and stabilizing agents for synthesis of gold nanoparticles (Chanda *et al*., 2010; Kim 2011; Mohamed *et al*., 2012, Kharissova *et al*., 2013).

Petalonia fascia is a brown marine seaweed found in cold-water environments, this species can survive in a variety of habitats. It has even been found in saline ponds and estuaries with soft bottoms, where the population are able to withstand large variations in salinity, temperature, turbidity, and current speed. This alga has been commonly used in various cultures for its nutritive and medicinal benefits (El Din *et al*., 2007; El-Shouny *et al*., 2017). It is a plentiful supply of

bioactive compounds, including polyphenols, flavonoids, amines, ketones and sulfated polysaccharides, which can play a potential role as a reducing, capping and stabilizing agents for the synthesis of 'AuNP', Additionally, as a brown seaweed; it contains the pigment fucoxanthin, which is well-known for its ability to reduce metal ions to produce gold nanoparticles (Shera and Banik 2021). Some investigations demonstrated biosynthesis of gold nanoparticles using marine seaweeds such as: *Sargassum wightii*, *Laminaria japonica*, *Gelidiella acerosa*, *Stoechospermum marginatum*, *Turbinaria conoides*, *Sargassum tenerrimum* (Singaravelu *et al*., 2007; Ghodake et al., 2011; Rajathi *et al*., 2012; Ramakrishna *et al*., 2016; Senthilkumar *et al*., 2019), but no study has demonstrated the biosynthesis of gold nanoparticles using Egyptian seaweeds (*Ulva linza* Linnaeus, *Ulva fasciata* Delile, *Ulva intestinalis* Linnaeus, *Petalonia fascia* (O.F.Müller) Kuntze and *Corallina offisinalis* Linnaeus); also, their antidiabetic potential has not been evaluated.

In this context, this study focuses on a simple, fast, and ecofriendly synthesizing 'AuNPs' using aqueous extracts of five different Egyptian seaweeds, *Ulva linza, Ulva fasciata, Ulva intestinalis, Petalonia fascia and Corallina offisinalis*, characterization of the synthesized *Petalonia fascia*- 'AuNPs' and evaluating their antidiabetic potential.

MATERIAL AND METHOD

Chemicals

Chloroauric acid (Gold chloride; $H[AuCl_4]$ was purchased from Sigma-Aldrich Chemicals. alpha-Glucosidase Inhibitor Screening Kit (Colorimetric) (ab284520) (K938), and α-Amylase Inhibitor Screening Kit (Catalog # K482-100) were obtained from BioVision, USA. All used chemicals were of analytical grade.

Seaweeds' collection

Five seaweed species of several divisions including, *Ulva linza*, *Ulva fasciata* and *Ulva intestinalis* (*Chlorophyta*), *Petalonia fascia* (*Phaeophyta*), and *Corallina officinalis* (*Rhodophyta*) (Figure 1) were collected from Alexandria, Egypt (El Shatby beach, Abu Qir Bay and Al Aanfushi bay) during March 2022. The seaweeds' samples were handpicked collected and washed with seawater to remove epiphytes, debris, foreign particles and sand particles. Then all samples were kept in an ice box and transported to the laboratory. Samples were cleaned thoroughly with tap water followed by distilled water then air dried and grounded to powder using an electrical blender. Samples were kept at 4°C until use. The collected seaweed samples were identified according to Aleem (1978), Kanaan and Belous (2016), and Guiry and Guiry (2022).

Preparation of seaweeds' aqueous extracts

Two grams from each powdered seaweed were separately dispensed in Ultra-pure water (100 mL) and heated for 10 min at 60℃ (Kannan *et al*., 2013) then filtrated using Whatman filter papers to obtain aqueous extracts (20 mg/mL) from each seaweed.

Screening of collected seaweed for the synthesis of gold nanoparticles

The samples' extracts were screened for their ability to produce 'AuNPs' as a green and eco-friendly approach. The detection of 'AuNPs' synthesis is recorded as a visual color change of the extracts to purple or ruby red and by UV-Vis spectroscopy at various periods for each seaweed. The following conditions proved to be ideal for producing the narrowest particle size distribution: 2 mL of each aqueous extract (20 mg/mL) was mixed separately

Figure 1. Morphological shapes of the studied five Egyptian seaweed collected from El Shatby Beach, Abu Qir Bay, and Al anfushi bay.

with 2 mL of chloroauric acid H[$AuCl_4$] solution (1 mM), the reaction combinations were mixed thoroughly and incubated in dark at 25±2.0℃ and observed periodically to register the time consumed for the first appearance of change in color indicating 'AuNPs' formation for each seaweed extract.

Large scale production of 'AuNPs' using Petalonia fascia extract

The reaction mixture was prepared by adding 200 mL of *P. latifolia* extract (20 mg/mL) to 200 mL H[$AuCl_4$] (1 mM), in a covered 500 mL conical flask and kept in a preheated water bath at 90°C for 10 min to speed up the formation of 'AuNPs'. The change of color of the reaction mixture was photographed at once. The bio-transformed gold chloride solution was separated by centrifugation for 15 min (15,000 rev min^{-1}) to extract any unbound components that weren't capping the 'AuNPs' and stored in the dark at 4℃ until needed for further analysis. The obtained 'AuNPs' were characterized using UV–vis spectroscopy, transmission electron microscopy, Fourier-transform infrared spectroscopy, and the crystallinity of formed gold metal was confirmed using X-ray diffraction. Moreover, antidiabetic activity was achieved using these generated 'AuNPs'.

Characterization of bio-produced gold nanoparticles

Screening by UV–vis spectroscopy: A JENWAY 7315, UK Spectrophotometer was set to scan absorbance for each sample from 400 to 700 nm using Milli-Q water as a baseline (Blank).

Transmission electron microscopy: A micrograph was taken using the JEOL-JEM transmission electron microscope (TEM) (JEOL-JEM-100CX II, Japan, Tokyo). A 3.0 mm diameter TEM copper coated carbon grid was loaded with 5 µL of the formed 'AuNPs' over a filter paper and allowed to dry at room temperature for 24 h. Next day, the grid is completely dried and carefully placed in the TEM holder using fine forceps. The electrons emitted by the gun were accelerated at 80 kV. The condenser, objective, and selected area apertures were all adjusted to get the best visualization of the sample over a computer monitor in the viewing chamber, after that the micrographs were captured.

X-ray diffraction pattern of formed 'AuNPs': A 500 µL of purified and concentrated 'AuNPs' was spread to form a thin film over approximately 1 cm on a 3 cm glass slide, then allowed to dry using hot-air gun. The 'AuNPs' sample was analyzed at Sohag University's X-ray Diffraction Laboratory using a Bruker D8 Advance diffractometer (Billerica, MA, USA) with a copper-sealed tube producing Cu kα radiation. The diffractometer uses a 40 kV, 40 mA generator to run at 1.5406 Å wavelength.

Fourier transform infrared spectroscopy (FT-IR): The functional groups on the surface of the biologically produced 'AuNPs' were investigated using FT-IR. Two samples were analyzed for comparability: the algal extract and the formed 'AuNPs' solutions, by placing the samples directly to a JASCO FT-IR spectrophotometer (FT-IR-6100; JASCO, Tokyo, Japan). Several scans (512) were completed in the spectral region of 4000–400 cm^{-1} in diffused transmittance mode (resolution, 4 cm^{-1}) to get a decent signal–to–noise ratio.

In vitro α -glucosidase inhibitory activity

The test samples, *Petalonia fascia* extract and 'AuNPs', were dissolved in DEMSO to a concentration of 100X, then diluted to 10X using α-Glucosidase Assay Buffer. The assay was carried out in accordance with the Alpha-Glucosidase Inhibitor Screening Kit (ab284520) manufacturer's instructions. Briefly, the samples were mixed with the provided substrate solution and test compounds or controls in a 96-well clear plate with flat bottom; appropriate blanks were included. To assess the inhibition of α-glucosidase enzyme, a total reaction volume of 200 µL at 37°C containing 0.1 U/mL of the enzyme was combined with 1.25 mM pNPG in either the inclusion or devoid of TN extracts (10 µg/mL). To determine the activity of the enzyme, the wavelength of absorption of each well was monitored at 410 nm using the kit's procedure. The prohibitive activity of α-glucosidase was presumed using the following formula:

Percentage of inhibition (%) = [(X_A − X_B) / X_A] × 100, where X_A is the wavelength of the control enzyme 'Acarbose' (100% enzyme activity) and X_B is the absorbance of the sample being tested.

***In vitro* α -amylase inhibitory action**

The assay followed the manufacturer's instructions regarding the α-amylase suppressor screening kit (Catalogue # K482-100) in 96-well microplate with flat bottom. The results were measured using a multi-well spectrophotometer (ELISA reader) at OD=405 nm in kinetic state for 20–25 min at ambient temperature.

RESULTS

Synthesis of 'AuNPs' from Collected Seaweeds

After exposing each aqueous extract of seaweeds to the chloroauric acid solution, its color changed

gradually to purple or ruby red, indicating the reduction of gold metal ion $[AuCl_4]^-$ into gold nanoparticles 'AuNPs' at different periods of time. As shown in Figure 2A, B, there were variations in the color change, which are mostly dependent on the seaweed extract's phytochemical components and reaction time (Rajeshkumar *et al*., 2013).

Spectral analysis verified that the color shift is formed by the gold nanoparticles' surface plasmon resonance (SPR) being excited by light flowing through them (Inbakandan *et al*., 2010). UV-vis spectroscopy was utilized to demonstrate the successful biofabrication of the formed 'AuNPs'. Spectral signatures of the gold nanoparticles from the five different seaweeds were first detected at different time intervals and wavelengths, as shown in Figure 2C. Variations were recorded in the peaks of SPR for synthesized 'AuNPs' as follows: *Petalonia fascia* (540 nm; 1.5 h), *Ulva linza* (540 nm; 5 h), *Ulva fasciata* (550 nm; 9 h), *Ulva intestinalis* (535 nm; 12 h), and *Corallina officinalis* (545 nm; 20 h). The result indicated the sharpest peak value of 'AuNPs' formed using *P*. *fascia* extract. Therefore, *P*. *fascia* was selected for further characterization and study. *Petalonia fascia* showed the highest and sharpest peak of 'AuNPs' among the five tested seaweeds, therefore, it was selected for further study.

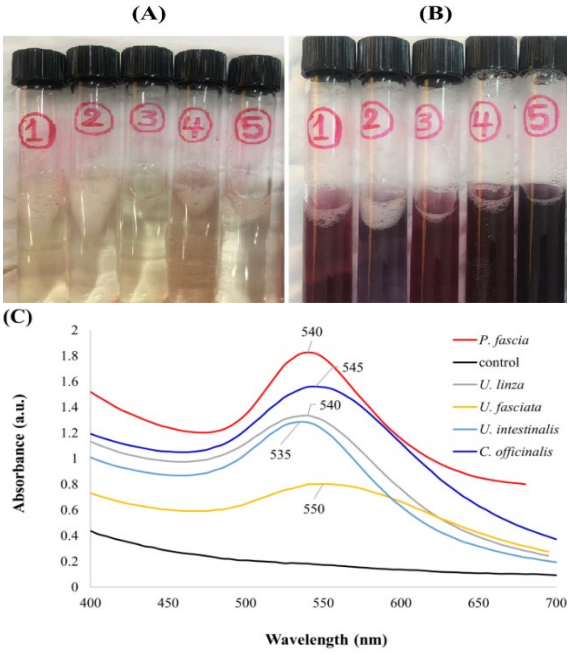


Figure 2. Color of seaweed extracts before and after formation of gold nanoparticles. Color of seaweed extracts at zero time before heating (A), Color change of extracts after AuNPs are formed (B), 1. *Ulva linza*, 2. *Ulva fasciata*, 3. *Ulva intestinalis*, 4. *Petalonia fascia*, and 5. *Corallina offisinalis*, and UV-vis spectroscopy of Egyptian seaweed extracts screened for synthesis of AuNPs (C).

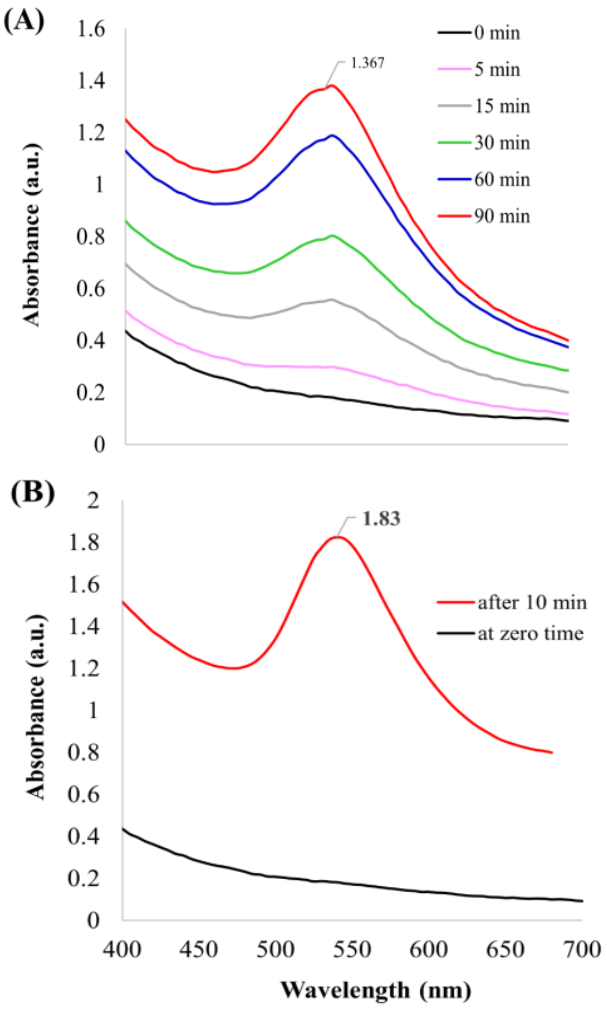
Characterization of *Petalonia*. *fascia*-mediated 'AuNPs'

A rapid method was applied for generating 'AuNPs' within 10 min by heating the reaction mixture at 90°C. This induced formation of the unique color of 'AuNPs' within few minutes and could be confirmed by UV-vis spectroscopy showing an absorbance at 1.83 and 540 nm, while without heating the absorbance reached only 1.38 after 90 min of starting the reaction (Figure 3).

Transmission Electron Microscopy: The dimensions and form of the synthesized gold nanoparticles were evaluated utilizing transmission electron microscopy (TEM). An equivalent size distribution histogram was also calculated using measurements of a significant number of nanoparticles (>100) (*>100*). The images obtained for the produced nanoparticles showed that all the particles analyzed were spherical-shaped, with a mean diameter of 9.02 ± 1.7 nm (Figure 4).

X-ray diffraction Analysis of *P. fascia*-AuNPs: Patterns from XRD were utilized to determine the crystallinity of the biosynthesized 'AuNPs". The diffractogram obtained from 'AuNPs' prepared using *P*. *fascia* extract is depicted in Figure 5. Based on XRD patterns, the formed NPs were found to be crystalline, showing characteristic peaks with position 2θ values of 38.39° (111), 44.54° (200), 64.89° (220), and 77.72° (311), these peaks correspond to the crystallographic planes of face-centered cubic (fcc) gold, confirming the fabrication of metal gold (Au^0) (JCPDS 1997).

Infrared Spectroscopy with the Fourier Transform Analysis: Spectral analysis of FTIR for two samples: the aqueous extract of the marine seaweed, and the produced 'AuNPs'; was performed to discover the putative biomolecules that promoted the reduction of gold ions and the capping of 'AuNPs'. The infrared spectrum of the water-based extract of *P*. *fascia* is demonstrated in Figure 6. We observed three strong peaks: a broad peak at 3450 cm^{-1} (characteristic of -OH stretching in alcohols or phenolic compounds), a sharp peak at 1631 cm^{-1} (characteristic of N-H stretch of primary amines), and a broad peak at 619 cm^{-1} (indicative of -OH out of bending). The synthesized AuNPs' IR spectra resembled the crude extract's, with slightly different wavelengths and intensities. After reducing gold ions, the peak at 619 cm^{-1} switched to 659 cm^{-1}, suggesting capping with 'AuNPs'.



(C)

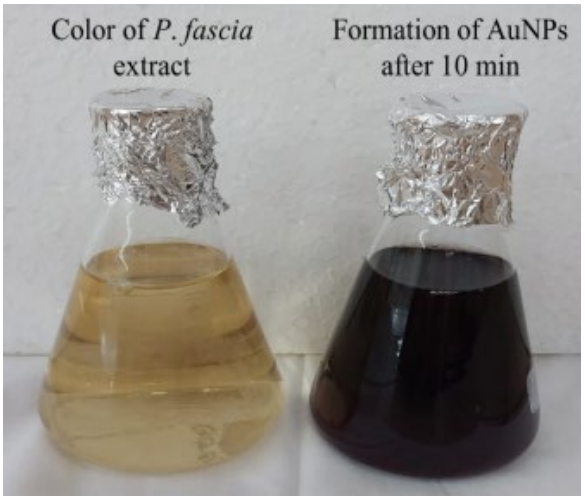


Figure 3. UV-vis spectroscopy of gold nanoparticles formed by *P. fascia* seaweed. Scanning of UV-vis spectroscopy of formed AuNPs from 0 to 90 min at 25±2.0℃ (A), UV-vis spectroscopy of formed AuNPs at 10 min after heating to 90℃ (B), and Color change of *P. fascia* extract after formation of AuNPs (C).

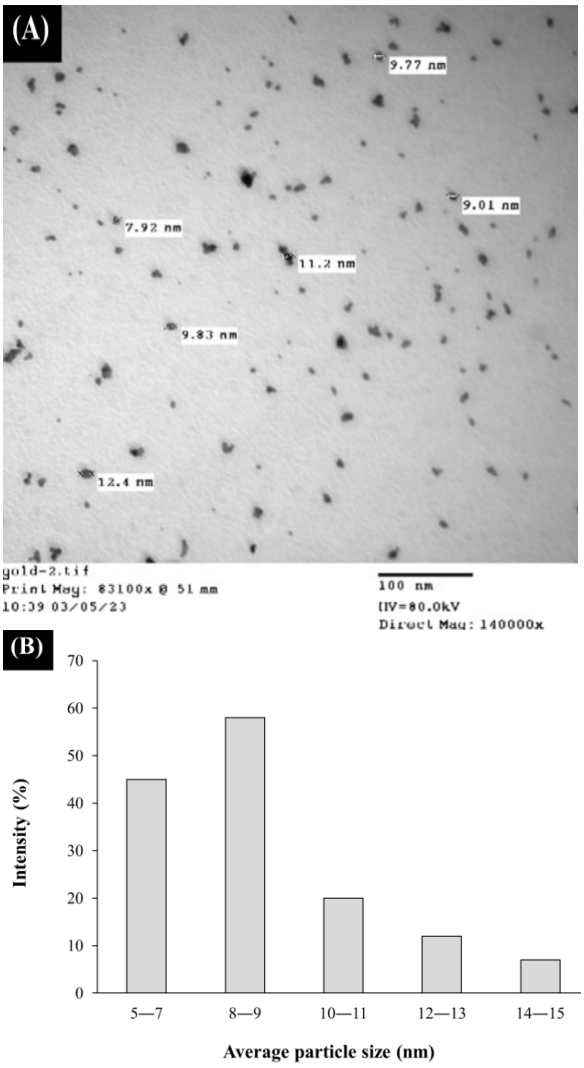


Figure 4. Biosynthesized gold nanoparticles using *P. fascia* seaweed extract. TEM micrograph of AuNPs showing anisotropic morphology at scale bar 100 nm (A), and particle size distribution (B).

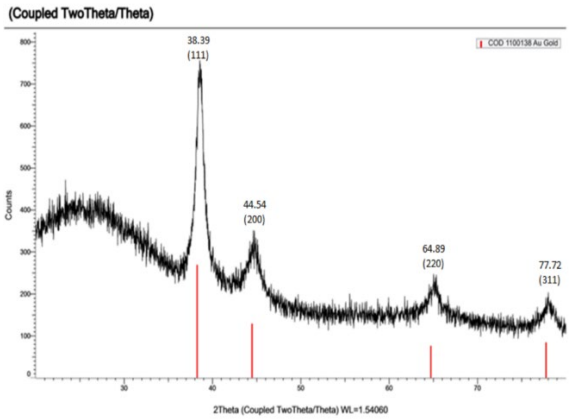


Figure 5. X-ray diffraction pattern of the AuNPs obtained from *Petalonia fascia*.

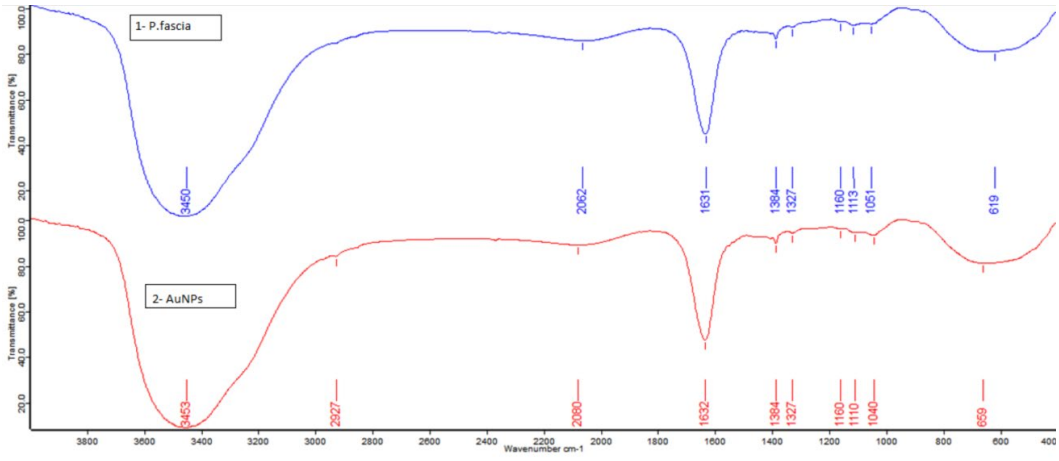


Figure 6. FT-IR analysis of *P. fascia* extract and bio formed AuNPs.

Antidiabetic Potential of the Produced 'AuNPs'

In our study, the suppression of α-glucosidase enzyme expression was measured at doses ranging from 20 to 100 mg/mL. Samples of 'AuNPs", *P. fascia* extract, and acarbose showed α-glucosidase inhibition activity in an increasing order from 20 to 100 mg/mL concentration. A maximum of 90.6%, 84%, and 87.1% inhibition of α-glucosidase activity was observed at 100 mg/mL concentration for 'AuNPs', P. *fascia* extract, and acarbose, respectively. IC50 values for 'AuNPs', *P. fascia* extract, and acarbose are indicated in Table 1. Also, the suppression of α-amylase activity by the produced 'AuNPs', *P. fascia* extract, and acarbose as a positive control was found to be dose-dependent from 20 to 100 mg/mL concentrations. A maximum of 87.4%, 82.8%, and 86.5% inhibition of α-amylase activity was observed at 100 mg/mL concentration for 'AuNPs', *P. fascia* extract, and acarbose, respectively as depicted in Figure 7. IC50 values for 'AuNPs', *P. fascia* extract, and acarbose were 0.312 ± 0.014, 0.515 ± 0.023, and 0.178 ± 0.008 mg/mL, respectively (Table 1).

DISCUSSION

Seaweeds are a source of certain compounds that are unique to these organisms (such as fucoidan, neutral glucan, alginic acid and guluronic) and have a variety of biological activities (such as anticoagulant, antifungal, antibacterial, and antifouling activity). Synthesis of gold nanoparticles is possible via extracellular and intracellular pathways (Ahluwalia and Goyal 2007). Thus, polysaccharides with sulphate and amide-bonded peptides can reduce gold ions to nanoparticles and stabilize 'AuNPs' in a water-based medium (Rajeshkumar *et al*., 2013).

Table 1. IC50 values of 'AuNPs', *P. fascia* extract and acarbose for α-glucosidase, and α-amylase inhibition.

Analyte	IC50 (mg/mL)	
	α -glucosidase	α -amylase
'AuNPs'	0.078 ± 0.003	0.312 ± 0.014
P. fascia extract	0.461 ± 0.017	0.515 ± 0.023
Acarbose	0.18 ± 0.007	0.178 ± 0.008

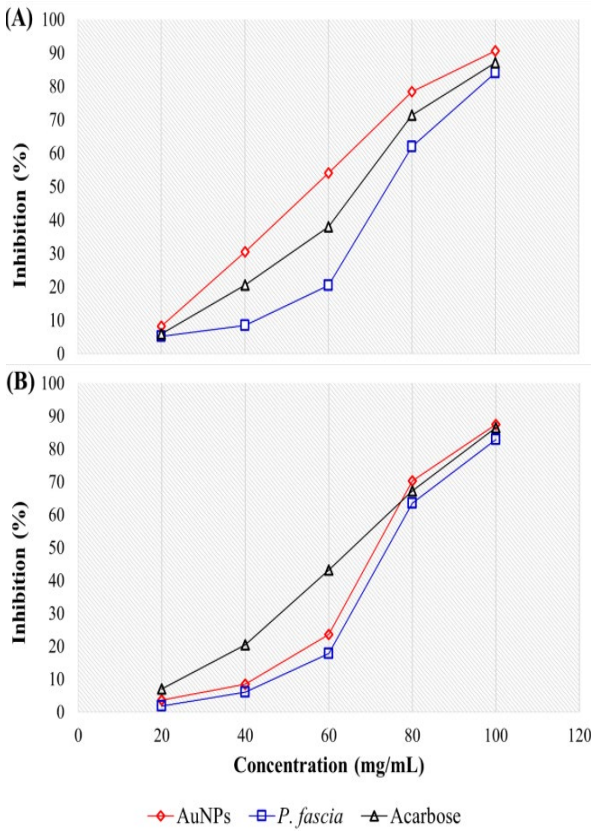


Figure 7. Percentage inhibition at different concentrations of AuNPs, *P. fascia* extract and Acarbose. α-glucosidase (A), and α-amylase assays (B).

The UV-vis spectroscopy confirmed the successful biofabrication of the 'AuNPs', showing spectral signatures of the gold nanoparticles from the five different seaweeds at various time intervals and wavelengths, dependent on the seaweed extract's phytochemical components and reaction time. Thus, the sharpest peak value of 'AuNPs' formed using *P. fascia* extract, indicating the highest 'AuNPs' concentration and the fastest reduction of gold ions (Ramakrishna *et al*., 2016). In our study, using *P. fascia* extract, the purple color was formed in the first 3 min of incubation, then changed gradually to dark purple after 10 min, indicating the completion of the reduction process. This color is characteristic to 'AuNPs' (Mubarak *et al*., 2011). Heating at 90℃ accelerated the time consumed for 'AuNPs' formation within 10 min, this was a very short time compared to other studies that used seaweed extracts for 'AuNPs' formation. For example, Princy and Gopinath (2018) reported 'AuNPs' synthesis starting at 2 h using the seaweed *Padina tetrastromatica*. To prove the importance of heating during the reaction, the reduction process and completion of 'AuNPs' formation was recorded by observing the variation of the color intensity and measuring the SPR band from 0 p to 90 min of the reaction at 25±2.0℃ and compared to performing the same procedures at 90℃. The spectra in Figure 3 show the difference between 'AuNPs' formation at 25±2.0℃ and 90℃, showing the effect of heating on accelerating the reaction rate completion. Heating accelerates the formation of 'AuNPs' using *P. fascia* extract due to increased kinetic energy, which enhances the rate of reaction. This leads to faster reduction of gold ions by biomolecules in the extract. Elevated temperatures also increase the solubility of these biomolecules, improving their interaction with gold ions and facilitating nucleation and growth of nanoparticles. Additionally, heating can promote the stabilization of nanoparticles by enhancing the capping efficiency of the biomolecules.

It was reported by many researchers that heating induces size and shape manipulation of 'AuNPs' (Sardar and Shumaker-Parry 2011; Badr *et al*., 2023). Seaweeds' aqueous extract is a very rapid method when compared with other biological sources such as bacteria (He *et al*., 2007), fungi (Singaravelu 2007), and plants (Annamalai *et al*., 2013) were employed in the reduction process to synthesize 'AuNPs' and took between 24 and 120 hours to complete the reduction of gold ions to gold nanoparticles. Rajeshkumar *et al*. (2013) reported 'AuNPs' synthesis using *Tubinaria conoides* seaweed, the reduction process completed at 24 h. In this study we report a new eco-friendly biological source *Petalonia fascia* that can be employed for rapid and substantial production of 'AuNPs', saving time and providing large quantities that can be directed into various applications.

The X-ray diffraction investigation revealed that the formed NPs were crystalline in nature, with characteristic peaks consistent with gold Bragg's reflections found in the diffraction pattern (Saxena and Harish, 2019; Abdelkader *et al*., 2022; Rey-Méndez *et al*., 2022). The alignment of these peaks with standard diffraction patterns for gold indicates the successful reduction of gold ions to elemental gold, affirming the crystalline nature of the synthesized nanoparticles. Such a well-defined fcc structure is characteristic of high-purity gold, and the sharpness of the peaks suggests good crystallinity and particle size uniformity. These findings are consistent with previous reports in the literature, validating the effectiveness of the seaweed extract-mediated synthesis method for producing crystalline 'AuNPs'.

The TEM analysis confirmed that the generated 'AuNPs' were sphere-shaped with an average diameter of 9.02 ± 1.7 nm. This uniformity in shape and size suggests a controlled synthesis process facilitated by the seaweed extract. The small size of the nanoparticles enhances their surface area, which is beneficial for catalytic activity and biological interactions. Such nanoscale dimensions are crucial for applications in biomedicine, as they may influence cellular uptake and bio-distribution, potentially leading to improved efficacy in therapeutic contexts.

Infrared spectroscopy with the Fourier transform (FTIR) spectral analysis of aqueous extract of the marine algae revealed the responsibility of compounds having hydroxyl functional groups in our extract to form the strong interaction with nanoparticles and production of stable 'AuNPs'. Overall, FTIR analysis provides insights into the chemical interactions and stabilization mechanisms that facilitate AuNP formation. This agreed with other researchers who indicated that the richness of brown seaweeds with hydroxyle groups (- OH) in proteins and polysaccharides; fucoidans, and alginate; made them a good candidate for synthesizing high stable gold nanoparticles (Chattopadhyay *et al*., 2010; Sinha *et al*., 2010; Mohankumar *et al*., 2012; Lumogdang and Teves, 2020). Also, FT-IR spectrum showed that *P. fascia* extract contains different secondary metabolites with various other functional groups

these compounds may work as AuNPs-reducing and -capping agents, which prevent agglomeration of the nanoparticles, stabilizing them in the colloidal solution (Rao *et al*., 2016). From our results, FTIR showed shifts in peak positions and changes in intensity, indicating interactions between the functional groups and gold ions during the reduction process.

The breakdown of carbohydrates by α-glucosidase and α-amylase and raises the postprandial glucose level in diabetic patients so diabetes risk can be decreased by controlling postprandial hyperglycemia and inhibiting the activity of these two crucial enzymes. Due to their potential for managing diabetes, 'AuNPs' have received significant attention in the search for innovative, safe, and effective anti-diabetic drugs (BarathManiKanth *et al*., 2010; Ansari *et al*., 2019, Abd El-Moaty *et al*., 2021; Omolaja *et al*., 2021; Veeramani *et al*., 2022).

The antidiabetic potential of the produced 'AuNPs' was demonstrated by their inhibition of α-glucosidase and α-amylase enzyme activities. The synthesized 'AuNPs' using *P. fascia* exhibited higher potential than the positive control acarbose. This agreed with previous studies reporting potent anti-diabetic activity of NPs synthesized from various seaweed extracts (Jaison *et al*., 2024). Also, it was reported that algal extracts and their bioactive components have antidiabetic properties as they block carbohydrate hydrolyzing enzymes *in vitro* and reduce blood glucose levels in random and postprandial blood glucose tests in animals (Agarwal *et al*., 2023).

The green synthetic 'AuNPs' derived from *Padina boergesenii*, a brown seaweed, demonstrated inhibitory efficacy against α-glucosidase inhibitors, with an IC50 value of 24 µg/mL (Senthilkumar *et al*., 2015). Another study tested the antidiabetic potential of Au-NPs synthesized from the marine alga *Gelidiella acerosa*, using acarbose as the control. Au-NPs exhibited the greatest α-amylase inhibitory action, having an IC50 value of 2.1 ± 0.01 compared to 1.7 ± 0.02 for acarbose (Senthilkumar *et al*., 2019). Algal-mediated nanoparticles have been shown to suppress α-amylase activity, leading to improved carbohydrate metabolism and lower glucose absorption. Also, previous studies reported the ability of marine algal extracts to inhibit α-amylase activity (Lordan *et al*., 2013). In our study, inhibition of α-amylase activity by the produced 'AuNPs', *P. fascia* extract and acarbose as a positive control was found to be dose dependent from 20 to 100 mg/mL concentration. The suppression of alpha amylase enzyme could limit the carbohydrate metabolism which also decreases the levels of glucose absorption. Previous studies reported the ability of marine algal extracts to inhibit α-amylase activity (Lordan *et al*., 2013). This inhibitory effect could be due to the large surface area-to-volume ratio of the bio synthesized 'AuNPs' (9.02 ± 1.7 nm), which enhances their interaction with enzymes and potentially inhibits their activity more effectively. Also, the bioactive compounds in *P. fascia* extract can act synergistically with 'AuNPs', enhancing enzyme inhibition. The functional groups on the surface of 'AuNPs' may facilitate stronger binding to the active sites of enzymes, leading to more effective inhibition. Moreover, gold nanoparticles are stable and biocompatible, which can contribute to their efficacy in biological systems compared to conventional inhibitors like acarbose. All these factors together can result in enhanced inhibitory effects on α-glucosidase and α-amylase compared to the standard control.

CONCLUSION

The biosynthesis of NPs from algae remains an appealing field of nanotechnology since it provides sustainability, non-toxicity, cost-effectiveness, and reliability. There is extensive literature and research in progress in this area. Future studies could focus on optimizing synthesis settings and selecting high-yielding algae strains. The rapid synthesis of 'AuNPs' using seaweed extracts, particularly *P. fascia*, offers a quick and efficient method compared to other biological sources. The synthesized 'AuNPs' show promising antidiabetic potential, highlighting the importance of further research into their biomedical applications. Algal-synthesized nanoparticles have potential for commercial medicinal therapies in the next few decades.

AUTHOR CONTRIBUTIONS

H. A. B., S. A. E., and M. O. contributed equally to this work. All authors were involved in Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, and Writing – review and editing.

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DATA AVAILABILITY STATEMENT

The original data presented in the current study are included in the article, further inquiries can be directed to the corresponding author.

CONFLICT OF INTEREST

The authors declare no competing interests.

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