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Original Article

Biosynthesis of Selenium Nanoparticles from *Turbinaria ornata*: Nutritional Assessment, Antioxidant Properties, and Cytotoxic Potential

Aishwariya Rao Muralidharan[1], Manoj Kumar Karuppan Perumal[2], Remya Rajan Renuka[2,*], Theebaa Anasamy[3], Antony Vincent Samrot[4,*]

[1]Center for Global Health Research, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, INDIA.
[2]Centre for Stem Cell Mediated Advanced Research Therapeutics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, INDIA.
[3]Department of Pharmacology, Faculty of Medicine, Manipal University College Malaysia, Persimpangan Batu Hampar, Bukit Baru, Melaka, MALAYSIA.
[4]Department of Microbiology, Faculty of Medicine, Manipal University College Malaysia, Persimpangan Batu Hampar, Bukit Baru, Melaka, MALAYSIA.

ABSTRACT

Background: Brown seaweeds like *Turbinaria ornata* (*T. ornata*) are rich in nutrients and bioactive compounds with therapeutic potential. While Selenium Nanoparticles (SeNPs) have gained attention for their biomedical applications, limited research exists on the green synthesis of SeNPs using *T. ornata*. The combined evaluation of its nutritional profile, antioxidant potential, and cytotoxicity remains underexplored. **Objectives:** This study investigated the nutritional profile, biosynthesis of *T. ornata* mediated Selenium Nanoparticles (To-SeNPs), antioxidant potential, and cytotoxicity of *T. ornata* extract. **Materials and Methods:** Nutritional profiling of *T. ornata* was performed using standard biochemical assays. To-SeNPs were synthesized using the aqueous extract of *T. ornata* and characterized via UV-Vis spectroscopy, X-Ray Diffraction (XRD), and Fourier-Transform Infrared Spectroscopy (FTIR). Antioxidant activities were evaluated through DPPH, hydrogen peroxide, FRAP, ABTS, and nitric oxide scavenging assays. Cytotoxicity was assessed using an MTT assay on A549 lung cancer cells. **Results:** Nutritional analysis revealed significant levels of carbohydrates (43.7%), ash (23.4%), moisture (83.62%), protein (5.4%), and lipids (1.9%). UV-vis spectroscopy confirmed SeNP formation with a peak at 300 nm. XRD analysis revealed 69.1% crystallinity, while FTIR identified potential capping agents. Biologically synthesized To-SeNPs demonstrated potent antioxidant activities across multiple assays. DPPH radical scavenging reached 88.33% at 50 µg/mL. Hydrogen peroxide scavenging showed 86.5% activity at the same concentration. FRAP, ABTS, and nitric oxide radical inhibition assays exhibited 86.22%, 86.33%, and 86.57% activities, respectively at 50 µg/mL. MTT assay on A549 cells revealed an IC_{50} value of 54.73 µg/mL for To-SeNPs. **Conclusion:** *T. ornata* possesses significant nutritional value, and its biosynthesised SeNPs exhibit potent antioxidant and anticancer properties, indicating their potential for therapeutic applications.

Keywords: *Turbinaria ornata*, Antioxidant, Selenium Nanoparticles, Cytotoxicity.

Correspondence:
Dr. Remya Rajan Renuka
Centre for Stem Cell Mediated Advanced Research Therapeutics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai-600077, Tamil Nadu, INDIA.
Email: remya.praveen5@gmail.com

Dr. Antony Vincent Samrot
Department of Microbiology, Faculty of Medicine, Manipal University College Malaysia, Persimpangan Batu Hampar, Bukit Baru-75150, Melaka, MALAYSIA.
Email: antonysamrot@gmail.com

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INTRODUCTION

Marine ecosystems represent a significant reservoir of biodiversity, encompassing a wide variety of organisms that offer considerable biological, nutritional, and medicinal value. Among these, marine algae, or seaweeds, have emerged as a promising resource due to their unique chemical composition and bioactivities.[1,2] Brown seaweeds, in particular, are widely recognized for their diverse applications in nutrition, pharmaceuticals, and nanotechnology. These macroalgae are a rich source of essential nutrients such as carbohydrates, proteins, lipids, vitamins, and minerals, as well as bioactive compounds like polyphenols, terpenoids, and polysaccharides, which contribute to their therapeutic properties.[3,4]

T. ornata, a species of brown seaweed commonly found in tropical and subtropical marine environments, has gained increasing scientific attention. This species is not only an abundant and renewable natural resource but also a potential candidate for

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use in nutraceuticals and therapeutic applications.[5] Numerous studies have highlighted its nutritional richness and bioactive properties, making it a viable functional food and a promising source of bioactive compounds for pharmaceutical use.[6] Despite this, comprehensive analyses of its nutritional value and potential applications in advanced fields such as nanotechnology are still limited. Nanotechnology, an interdisciplinary field at the interface of biology, chemistry, and materials science, has opened new avenues for developing eco-friendly and sustainable solutions in healthcare and environmental sciences.[7] Among the various nanoparticles studied, SeNPs have gained prominence due to their remarkable antioxidant, anti-inflammatory, and anticancer properties. Selenium is an essential trace element that plays a critical role in various biological processes, including the neutralization of oxidative stress and modulation of immune responses.[8] However, conventional methods of synthesizing SeNPs often involve toxic chemicals, raising concerns about environmental safety and biocompatibility.

Green synthesis of selenium nanoparticles using marine algae offers a sustainable and eco-friendly alternative.[9] Marine algae act as natural reducing and stabilizing agents, facilitating nanoparticle synthesis without the use of harmful chemicals. This approach not only reduces the environmental footprint of nanoparticle production but also enhances the bioactivity of the synthesized nanoparticles due to the presence of capping agents derived from algal metabolites.[10] The potential of *T. ornata* for synthesizing SeNPs represents an innovative approach to developing biologically active nanomaterials. Oxidative stress, caused by an imbalance between Reactive Oxygen Species (ROS) and antioxidants, is implicated in the progression of various diseases, including cancer, cardiovascular disorders, and neurodegenerative conditions. Antioxidants derived from natural sources, such as marine algae, have garnered significant attention for their ability to scavenge free radicals and mitigate oxidative damage.[11] Selenium nanoparticles, owing to their high surface area and functional versatility, are particularly effective in neutralizing ROS and preventing oxidative damage at the cellular level. Therefore, investigating the antioxidant potential of To-SeNPs is crucial for understanding their therapeutic implications. Furthermore, cytotoxicity studies play a pivotal role in evaluating the safety and efficacy of newly synthesized nanomaterials. The present study aims to bridge the gap in understanding the nutritional value, biosynthesis, characterization, antioxidant potential, and cytotoxic effects of To-SeNPs. By employing a multi-faceted approach, this research seeks to elucidate the bioactive properties of *T. ornata* and its synthesized SeNPs, highlighting their potential applications in nanotechnology, nutrition, and medicine. The findings of this study are expected to contribute to the marine natural products and their role in advancing sustainable therapeutic innovations.

MATERIALS AND METHODS

Collection and Processing of *Turbinaria ornata*

Fresh *T. ornata* seaweed was collected from Rameshwaram, Tamil Nadu and thoroughly washed with running tap water to remove dirt, salt, and debris, followed by rinsing with distilled water. The cleaned seaweed was shade-dried for 5-7 days at room temperature, powdered using a mechanical grinder, and stored for further use. For extract preparation, 10 g of the powdered seaweed was boiled in 100 mL of distilled water for 30 min at 80°C, filtered using Whatman No. 1 filter paper, and stored at 4°C for subsequent experiments.[12]

Nutritional Profiling of *Turbinaria ornata*

Moisture Content

The moisture content was determined by the oven-drying method. Fresh samples of T. ornata were weighed and placed in a hot air oven maintained at 105 ± 2 °C until a constant weight was obtained. The difference between the initial fresh weight and the final dry weight was used to calculate the percentage of moisture content.[14]

Ash Content

The total ash content was determined using a muffle furnace. A known weight of the dried seaweed sample was placed in pre-weighed crucibles and incinerated at 600 °C for 4 hours until a white or grey ash was obtained. After cooling in a desiccator, the crucibles were reweighed, and the ash content was expressed as a percentage of the dry weight.[14]

Lipid Content

Lipids were extracted using the Soxhlet extraction method. Approximately 2–5 g of dried powdered seaweed was packed into a thimble and subjected to extraction with acetone as the solvent for 6–8 hours. The solvent was evaporated, and the residue was dried to a constant weight. The lipid content was calculated as a percentage of the dry weight of the sample.[14]

Protein Content

Protein content was estimated by the Kjeldahl method.[14] A known weight of the dried sample was digested with concentrated sulfuric acid (H_2SO_4) in the presence of a catalyst mixture (usually copper sulfate and potassium sulfate). The digested material was then neutralized with sodium hydroxide, followed by distillation of the liberated ammonia into a boric acid solution. The ammonia content was determined by titration with standardized hydrochloric acid. The nitrogen value obtained was multiplied by a conversion factor of 6.25 to estimate the crude protein content.

Carbohydrate Content

The total carbohydrate content was calculated by the difference method. The percentage values of moisture, protein, lipid, and

ash contents were summed, and the total was subtracted from 100 to obtain the carbohydrate percentage on a dry weight basis.[14]

Biosynthesis of *T. ornata*-mediated Selenium Nanoparticles (To-SeNPs)

To-SeNPs were synthesized using a 10 mM sodium selenite (Na_2SeO_3) solution as the precursor. 50 mL volume of the *T. ornata* aqueous extract was mixed with an equal volume of the sodium selenite solution and stirred at 120 rpm at room temperature for 24 hr. The color change from yellow to reddish-orange confirmed the formation of selenium nanoparticles. The nanoparticles were collected by centrifugation at 10,000 rpm for 20 min, washed with distilled water to remove unreacted components, air-dried at 50 °C, and stored in airtight containers for further characterization.[13]

Characterization of To-SeNPs

UV-Visible Spectroscopy

The formation of To-SeNPs was confirmed using UV-Visible spectroscopy. The absorbance of the nanoparticle solution was measured in the wavelength range of 350–550 nm at room temperature.[15] The appearance of characteristic surface plasmon resonance (SPR) peaks indicated the successful synthesis of To-SeNP.

X-Ray Diffraction

The crystalline structure and phase of To-SeNPs were determined using X-ray diffraction. Powdered samples were analyzed using Cu Kα radiation (λ = 1.5406 Å). Diffraction patterns were recorded over a 2θ range of 10°–80°, and the crystallite size was estimated. The observed peaks were compared with standard reference patterns to confirm the crystal phase.[15]

Fourier Transform Infrared Spectroscopy

FTIR spectroscopy was performed to identify functional groups on the surface of To-SeNPs and to determine the biomolecules responsible for capping and stabilization. Dried nanoparticle samples were mixed with potassium bromide (KBr) to prepare pellets. Spectra were recorded in the range of 4000–400 cm^{-1}. Peaks corresponding to functional groups such as –OH, –COOH, and –NH suggested the presence of biomolecules interacting with the nanoparticles.[15]

Antioxidant Activity Assays

DPPH Assay

The antioxidant activity of To-SeNPs was evaluated using the DPPH free radical scavenging assay.[16] To-SeNP solutions at concentrations ranging from 25 to 125 µg/mL were mixed with 0.1 mM DPPH solution in methanol in equal volumes and incubated in the dark for 30 min. Absorbance was measured at 517 nm, and the percentage of radical scavenging activity was calculated using a standard formula. Cytotoxicity studies were performed using the MTT assay on A549 Cells were seeded in 96-well plates at a density of 1×10^4 cells per well, treated with To-SeNPs at various concentrations (10-100 µg/mL) for 48 hr, followed by MTT treatment, and absorbance was measured at 570 nm after dissolving formazan crystals in Dimethyl Sulfoxide (DMSO).

Hydrogen Peroxide Assay

The Hydrogen Peroxide Radical Scavenging Assay, To-SeNPs were tested at concentrations ranging from 10-50 µg/mL. The reaction mixture consisted of To-SeNPs and 40 mM hydrogen peroxide prepared in phosphate buffer (pH 7.4). After incubation at room temperature for 10 min, absorbance was measured at 230 nm, and the percentage of scavenging activity was calculated.[16]

FRAP Assay

The FRAP assay was performed to determine the reducing potential of To-SeNPs. The assay was conducted at concentrations of 10-50 µg/mL. To-SeNPs were mixed with FRAP reagent (300 mM acetate buffer, 10 mM TPTZ in HCl, and 20 mM $FeCl_3 \cdot 6H_2O$), and the reaction was incubated for 30 min at 37°C. Absorbance was recorded at 593 nm, and reducing power was quantified using standard calibration curves.[16]

ABTS Assay

The ABTS assay was used to assess the scavenging ability of To-SeNPs at concentrations of 10-50 µg/mL. ABTS radical cations were generated by reacting 7 mM ABTS with 2.45 mM potassium persulfate in the dark for 12 hr. The prepared ABTS solution was diluted with ethanol to achieve an absorbance of 0.7 at 734 nm. To-SeNPs were mixed with the ABTS solution, incubated for 30 min, and absorbance was measured at 734 nm to calculate radical scavenging activity.[16]

Nitric Oxide Assay

The Nitric Oxide Radical Inhibition Assay was performed using the Griess-Ilosvay reaction. Sodium nitroprusside (5 mM) was incubated with To-SeNPs at concentrations ranging from 10-50 µg/mL in phosphate buffer (pH 7.4) at 25 °C for 150 min. After incubation, the Griess reagent (sulfanilamide and naphthyl ethylenediamine dihydrochloride) was added, and the absorbance was measured at 546 nm. The percentage inhibition of nitric oxide radicals was calculated.[16]

Cytotoxicity Studies

Cell Culture and MTT Assay

Cytotoxicity studies were conducted on A549 lung cancer cells using the MTT assay. A549 cells were cultured in Dulbecco's Modified Eagle Medium supplemented with 10% fetal bovine serum and penicillin-streptomycin (1%) at 37 °C in a humidified incubator with 5% CO_2. Cells were seeded in 96-well plates at a density of 1×10^4 cells per well and allowed to adhere overnight.

The cells were then treated with varying concentrations of To-SeNPs (10-100 µg/mL) for 48 hr. Following treatment, 20 µL of MTT solution (5 mg/mL) was added to each well and incubated for 4 hr at 37 °C. The resulting formazan crystals were dissolved in DMSO, and absorbance was measured at 570 nm using a microplate reader to determine cell viability.[17]

Ethical Consideration and Patient Consent

This study did not require ethical approval and patient consent as it does not involve human participants or animal subjects.

RESULTS

Nutritional Profile of *Turbinaria ornata*

The nutritional analysis of *T. ornata* revealed a diverse composition of essential nutrients. The moisture content was found to be 83.62%, which is typical for marine algae and contributes to their fresh weight. The high ash content of 23.4% indicates a rich mineral composition, significantly higher than that of terrestrial plants. This suggests that *T. ornata* could be a valuable source of essential minerals in the diet. Carbohydrates were the predominant macronutrient, constituting 43.7% of the dry weight. This high carbohydrate content underscores the potential of *T. ornata* as an energy source and its possible applications in food and feed industries. The protein content was determined to be 5.4%, which is within the typical range for brown seaweeds (5-24% of dry weight). While not as high as some red or green seaweeds, this protein content still represents a noteworthy contribution to the overall nutritional value. The lipid content was found to be 1.9%, which is consistent with the generally low lipid content (typically <5% of dry weight) observed in most seaweeds. Despite the low percentage, seaweed lipids are often rich in polyunsaturated fatty acids, which could contribute to the nutritional value of *T. ornata*. These findings highlight the potential of *T. ornata* as a nutrient-dense food source, particularly rich in carbohydrates and minerals, with moderate amounts of protein and low fat content as shown in Table 1.

Biosynthesis and Characterization of To-SeNPs

The biosynthesis of SeNPs using *T. ornata* extract was successfully achieved, as evidenced by the characteristic color change of the reaction mixture. The UV-Visible absorption spectrum of selenium nanoparticles synthesized using *T. ornata* extract at 3, 12 and 24 hr shows a small but distinct peak around 300 nm. This peak corresponds to the surface plasmon resonance of the iron nanoparticles, indicating their formation. The gradual decline in absorbance beyond 300 nm suggests the absence of significant aggregation and confirms the stability of the synthesized nanoparticles as shown in Figure 1A.

The FTIR spectrum of biosynthesized nanoparticles using *Turbinaria ornata* extract exhibits distinct peaks at 2342.36 cm^{-1}, 1604.38 cm^{-1}, 1405.47 cm^{-1}, 1096.14 cm^{-1}, and 720.75 cm^{-1}. The peak at 1604.38 cm^{-1} corresponds to C=C stretching vibrations of aromatic compounds, while the peak at 1096.14 cm^{-1} indicates C-O stretching of polysaccharides or alcohols. The absorption band at 2342.36 cm^{-1} suggests the presence of CO_2-related vibrations. The peak at 720.75 cm^{-1} may be associated with metal-ligand interactions, confirming the role of biomolecules in nanoparticle stabilization as shown in Figure 1B.

XRD pattern of the biosynthesized nanoparticles exhibits sharp and well-defined peaks at specific 2θ values, indicating their crystalline nature. The characteristic diffraction peaks observed at planes (100), (101), (110), (201), (202), (113), and (301) correspond to the crystalline phases of the nanoparticles. The highest intensity peak at (101) suggests a dominant orientation, confirming the structural properties of the synthesized material. The presence of multiple diffraction peaks indicates a well-ordered crystalline structure, further validating the successful synthesis of nanoparticles as shown in Figure 1C.

Antioxidant Activity of To-SeNPs

The antioxidant activity of *T. ornata* extract and To-SeNPs was evaluated using the DPPH radical scavenging assay (Figure 2A). The results demonstrated a concentration-dependent increase in radical scavenging activity for both treatments. At lower concentrations (100-200 µg/mL), *T. ornata*-SeNPs exhibited slightly higher antioxidant activity than the extract alone. As the concentration increased, To-SeNPs showed a significantly higher scavenging effect, approaching the antioxidant capacity of the standard (Vitamin C) at 500 µg/mL.

The enhanced radical scavenging activity of To-SeNPs suggests that selenium nanoparticle incorporation improves the antioxidant potential of the seaweed extract. The statistical significance of the results is indicated by asterisks (**p<0.05, **p<0.01, ***p<0.001), highlighting the improved efficacy of To-SeNPs in neutralizing free radicals. The hydrogen peroxide scavenging assay revealed similar trends, with To-SeNPs showing 86.5% scavenging activity at 50 µg/mL (Figure 2B). This indicates the nanoparticles' capacity to neutralize hydrogen peroxide, a potential source of oxidative damage in biological systems. In the FRAP assay (Figure 2C), To-SeNPs demonstrated strong reducing power, with 86.22% activity at 50 µg/mL. This suggests that the nanoparticles can donate electrons to reduce oxidized intermediates in lipid peroxidation processes. The

Table 1: Nutritional composition of *Turbinaria ornata*.

Parameter	Value
Moisture content	83.62%
Ash content	23.4% (DW)
Carbohydrates	43.7% (DW)
Protein	5.4% (DW)
Lipids	1.9% (DW)

ABTS (Figure 2D) and nitric oxide radical inhibition assays (Figure 2E) further confirmed the broad-spectrum antioxidant activity of To-SeNPs, with 86.33% and 86.57% inhibition rates at 50 µg/mL, respectively. These results collectively indicate that To-SeNPs possess potent free radical scavenging abilities, which may contribute to their potential therapeutic effects by mitigating oxidative stress-induced cellular damage (Figure 3).

Cytotoxicity Studies

MTT Assay on A549 Cells

The cytotoxic effect of To-SeNPs on A549 cells was evaluated using the MTT assay (Figure 3A). Exposure to To-SeNPs for 24 h resulted in a dose-dependent reduction in cell viability. Untreated control cells maintained nearly 100% viability, whereas treatment with 10 and 20 µg/ml caused only slight decreases (~90% and ~80% viability, respectively). A progressive decline was observed at higher concentrations, with ~70% viability at 40 µg/ml, ~50–55% at 60 µg/ml, and further reductions to ~35% and ~25% at 80 and 100 µg/ml, respectively. The IC_{50} value was calculated as 54.7 ± 4.2 µg/ml, confirming a significant growth-inhibitory effect of To-SeNPs against A549 cells.

The microscopic analysis of untreated and To-SeNPs-treated cells further supports the MTT assay findings. In the untreated group, cells exhibit a dense monolayer with normal morphology, maintaining their elongated and adherent structure. In contrast, cells exposed to To-SeNPs (76 µM/m) display significant morphological changes, including cell shrinkage, rounding, detachment, and loss of adherence. These alterations indicate reduced cell viability and possible induction of cytotoxic effects. The increased number of rounded and floating cells in the To-SeNPs-treated group suggests apoptosis or necrosis as the primary mode of cell death.

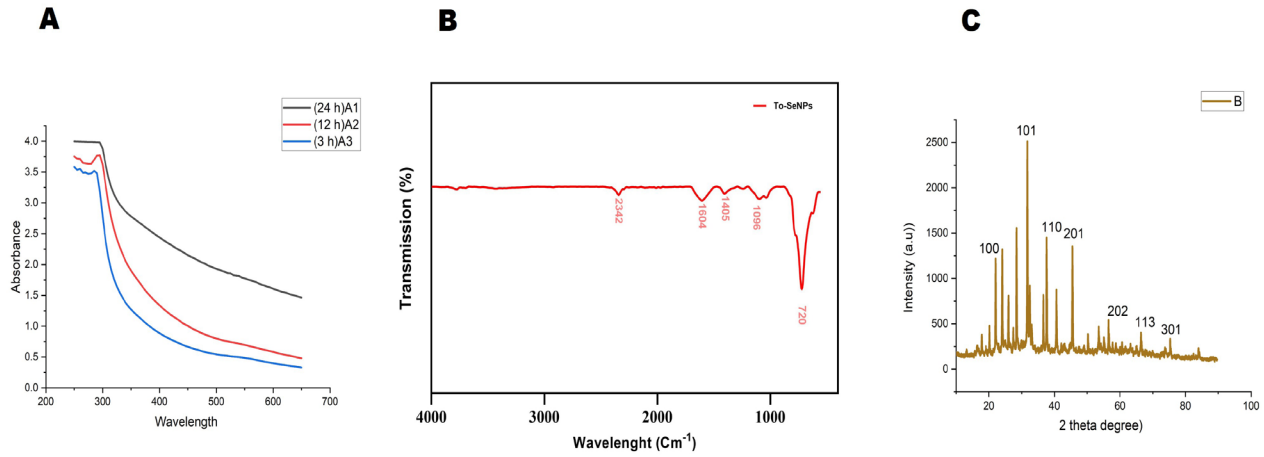

Figure 1: Physicochemical characterization of To-SeNPs. A) UV-Vis absorption spectra, B) FTIR, and C) XRD pattern.

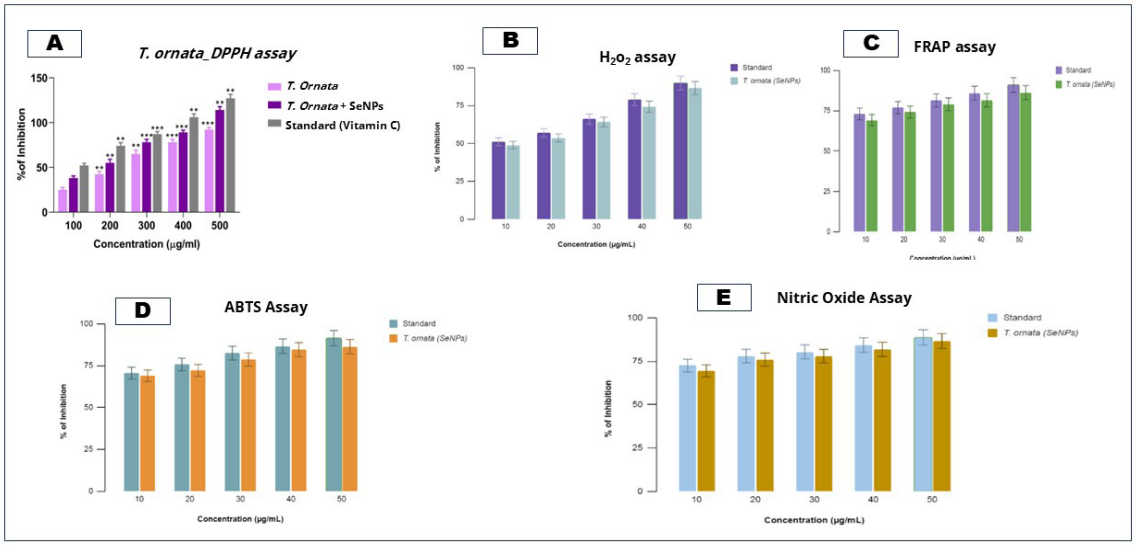

Figure 2: Antioxidant potential of To-SeNPs against A) DPPH, B) H_2O_2, C) FRAP, D) ABTS, and E) Nitric oxide.

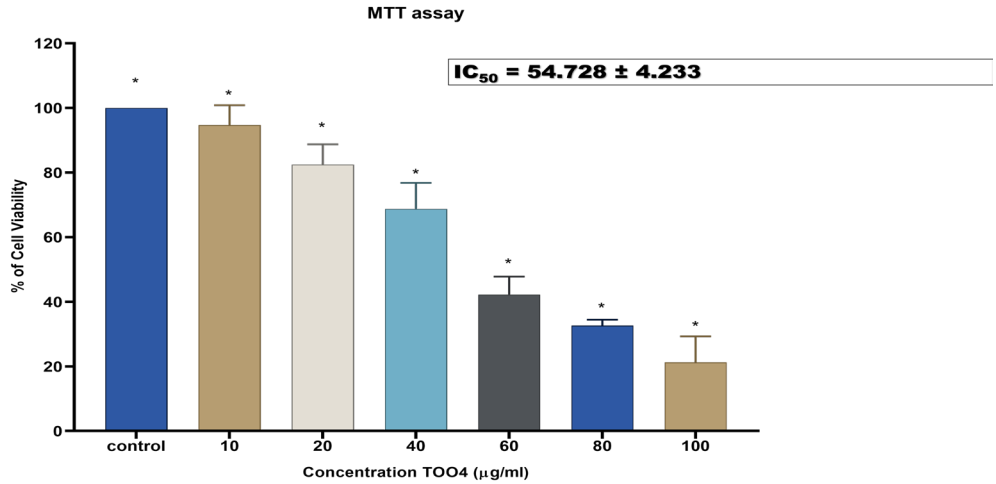

Figure 3: A) Cytotoxic effect of To-SeNPs on A549 cells.

DISCUSSION

The present study highlights the nutritional, phytochemical, and biomedical potential of *T. ornata* and To-SeNPs. The findings align with previous research demonstrating the diverse bioactive composition of brown seaweeds and their role in biomedical applications. The nutritional analysis revealed that *T. ornata* is a rich source of carbohydrates (43.7% dry weight), minerals (23.4% ash), and moderate protein content (5.4%), consistent with prior studies on brown algae.[17] The high ash content underscores the mineral-rich nature of *T. ornata*, potentially offering essential micronutrients such as iodine, calcium, magnesium, and iron. Although the lipid content was low (1.9%), previous reports suggest that brown algae lipids are rich in polyunsaturated fatty acids, which exhibit cardioprotective and anti-inflammatory effects.[18]

The successful biosynthesis of Selenium Nanoparticles (To-SeNPs) was confirmed by UV-Visible spectroscopy, FTIR, and XRD analyses. The characteristic UV-vis absorption peak at 300 nm aligns with previous reports on selenium nanoparticles synthesized from *Polycladia myrica* extracts.[19] FTIR analysis revealed functional groups such as C=C (1604 cm^{-1}) and C-O (1096 cm^{-1}), indicating the involvement of biomolecules in nanoparticle stabilization. XRD analysis confirmed the crystalline nature of To-SeNPs, with diffraction peaks matching those of selenium nanocrystals.[20] These findings are consistent with earlier studies suggesting that seaweed-mediated nanoparticles exhibit enhanced stability and biocompatibility due to natural capping agents.[21]

To-SeNPs demonstrated potent antioxidant activity across multiple assays (DPPH, FRAP, ABTS, nitric oxide scavenging), with scavenging efficiencies exceeding 85% at 50 µg/mL. These results correlate with studies indicating that selenium nanoparticles enhance enzymatic and non-enzymatic antioxidant defense mechanisms.[22] The antioxidant capacity of To-SeNPs could be attributed to their nano-size, high surface-to-volume ratio, and the presence of polyphenolic compounds from *T. ornata*, which synergistically improve radical scavenging ability.[23] The MTT assay revealed that To-SeNPs exhibited a dose-dependent cytotoxic effect on A549 lung cancer cells, with enhanced toxicity compared to *T. ornata* extract alone. These findings are in agreement with previous studies demonstrating that selenium nanoparticles induce apoptosis via oxidative stress, mitochondrial dysfunction, and caspase activation.[24] The morphological changes observed under microscopy, including cell shrinkage and loss of adherence, further support the apoptotic nature of cell death. Selenium nanoparticles are known to modulate ROS levels, activate tumor suppressor genes, and inhibit cancer cell proliferation, making them promising candidates for anticancer therapy.[25]

Given their antioxidant and cytotoxic properties, To-SeNPs could serve as a potential therapeutic agent for cancer treatment and oxidative stress-related disorders. However, further studies are required to explore the underlying molecular mechanisms, *in vivo* efficacy, and toxicity profiles of To-SeNPs. Future research should also focus on optimizing nanoparticle size, dose, and targeted delivery mechanisms to enhance therapeutic outcomes while minimizing side effects.[26]

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ABBREVIATIONS

T. ornata: *Turbinaria ornata*; **SeNPs:** Selenium Nanoparticles; **To-SeNPs:** *T. ornata* derived Selenium Nanoparticles; **XRD:** X-ray Diffraction; **FTIR:** Fourier Transform Infrared; **DPPH:** Diphenyl Picryl Hydrazine; **FRAP:** Ferric Reducing Antioxidant Potential; **ABTS:** 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); **MTT:** 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium

bromide; **ROS:** Reactive Oxygen Species; **DMSO:** Dimethyl sulfoxide.

SUMMARY

This comprehensive study on *T. ornata* has provided valuable insights into its nutritional value, the biosynthesis and properties of selenium nanoparticles derived from it, and their biological activities. The nutritional analysis revealed *T. ornata* as a rich source of carbohydrates and minerals, with moderate protein content. The successful biosynthesis of to-senps using *T. ornata* extract demonstrates an eco-friendly approach to nanoparticle production. The characterized nanoparticles exhibited potent antioxidant activities across multiple assays, suggesting their potential applications in combating oxidative stress-related disorders. The cytotoxicity studies revealed the selective antiproliferative effects of To-SeNPs against A549 lung cancer cells. These findings collectively suggest that to-senps contain bioactive compounds that need further investigation for potential therapeutic applications, particularly in cancer treatment and as antioxidant agents. Future research should focus on isolating and characterizing the specific compounds responsible for the observed antioxidant and cytotoxic effects. Additionally, mechanistic studies are needed to elucidate the molecular pathways involved in the biological activities of To-SeNPs. In conclusion, this study contributes to the potential of marine algae as a source of novel bioactive compounds and nanomaterials with therapeutic applications. The findings highlight the importance of continued exploration of marine biodiversity in the search for novel bioactive agents and highlights the potential of *T. ornata*.

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