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HARNESSING *Turbinaria decurrens* FOR ECO-FRIENDLY GOLD NANOPARTICLES SYNTHESIS: EXPLORING ANTIBACTERIAL AND ANTICANCER

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ABSTRACT

The essential nature of green synthesis for gold nanoparticles (AuNPs) stems from their distinct physicochemical properties, which enable their use in various applications. This research presents an environmentally conscious method for synthesizing AuNPs using an aqueous extract from the brown alga, *Turbinaria decurrens*, collected from Ambon Bay waters, Indonesia. The study pursued two main goals: to develop a sustainable production route and to assess the antibacterial and anticancer effectiveness of the resulting nanoparticles. The synthesis involved reducing chloroauric acid with the algal extract. The synthesis of AuNPs was verified using UV-vis spectroscopy, which identified a distinct Surface Plasmon Resonance (SPR) peak at 549 nm. Furthermore, FTIR analysis demonstrated that the organic compounds present in the *T. decurrens* extract served a dual purpose, functioning as both stabilizing and capping agents for the nanoparticles. Temperature, incubation period, and precursor-to-extract ratio determined the formation rate, size, and morphology of the synthesized AuNPs. Bioactivity analysis demonstrated that AuNPs exhibited antibacterial capacity against various strains of human pathogens and anticancer activity, inhibiting breast cancer cells. These findings confirm the versatile abilities of AuNPs synthesized from an aqueous extract of *T. decurrens*, providing a promising treatment for infectious and cancer diseases. This study provides a cost-effective, scalable, and environmentally friendly nanoparticle synthesis platform based on marine resources. Furthermore, this work aligns with SDG-3: Good Health and Well-Being by advancing safer therapeutic strategies and SDG-12: Responsible Consumption and Production through green synthesis particles.

Keywords: Antibacterial Agent, Anticancer Agent, Gold Nanoparticles, Green Synthesis, *Turbinaria decurrens*

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INTRODUCTION

Various methods exist for synthesizing nanoparticles (NPs), but the utilization of algae, fungi, bacteria, and plants is preferred due to their cost-effectiveness, energy efficiency, non-toxic nature, minimal chemical use, eco-friendliness, and reliability.[1] Macroalgae serve as efficient, cost-effective, and sustainable model organisms for the extracellular production of nanoparticles (NPs). This process involves the reduction of metal precursors and the regulated transformation of bulk materials into nano-sized particles.[2] Specifically, the use of macroalgae has been validated as a robust method for the eco-friendly biosynthesis of gold nanoparticles (AuNPs).[3] Brown algae are particularly effective precursors for green synthesis due to their high concentration of phytochemicals, which function as both reducing and stabilizing agents during the reaction.[4] The versatility of AuNPs allows for their application across numerous sectors, such as diagnostic imaging, targeted therapy, photothermal cancer treatment, biosensing, drug and nucleic acid delivery, pathogen detection, and biocatalysis.[5] This study addresses

the gaps by utilizing *T. decurrens* as a novel and sustainable marine resource for AuNPs synthesis while systematically linking with nanoparticle properties and bioactivities. This research strongly aligns with global sustainability properties. It supports SDG 3 (Good Health and Well-Being) through the development of innovative antibacterial and anticancer agents, and the green synthesis approach contributes to SDG 12 (Responsible consumption and production). Collectively, this study highlights the potential of marine-derived green nanotechnology to bridge environmental sustainability and healthcare solutions.

EXPERIMENTAL

Brown alga *Turbinaria decurrens* Bory was collected from Ambon Bay, Maluku, Indonesia. Dried algal powder (10 g) was extracted with 100 mL Milli-Q water under continuous stirring for 2 h, followed by heating at 60°C for 30 min. After cooling, the extract was filtered and stored at 4°C for subsequent use. AuNPs were synthesised by mixing the aqueous *T. decurrens* extract with 1.0 mM $HAuCl_4$ at a 1:1 (v/v) ratio under continuous stirring at room temperature, with the change in colour from pale yellow to red wine serving as an indicator of nanoparticle formation. To optimise synthesis conditions, extract-to-precursor ratios (2:8 to 8:2, v/v) and temperatures (25, 37, and 50°C) were systematically evaluated. The synthesized AuNPs were characterised by UV–Visible spectrophotometry, Fourier-transform infrared spectroscopy (FTIR), Transmission electron microscopy (TEM), and X-ray diffraction (XRD), along with particle size and zeta potential analyses. Antibacterial activity was assessed using the agar well diffusion method against *Staphylococcus aureus* (ATCC 13420), *Escherichia coli* (ATCC 25922), *Bacillus subtilis* (ATCC 6051), and *Mycobacterium smegmatis* (ATCC 19420), with ampicillin and rifampicin as positive controls. Cytotoxicity was evaluated in MCF-7 breast cancer cells using an MTT assay.

RESULTS AND DISCUSSION

Biosynthesised AuNPs

Gold nanoparticles (AuNPs) were prepared via an eco-friendly method using water based derived from *Turbinaria decurrens* (Fig.-1A). Nanoparticle formation was indicated within 30 min by a colour change from light yellow (extract alone; Fig.-1B) to wine red (Fig.-1C), consistent with the reduction of gold (Au^{3+}) ions by the bioactive component in the extract. UV-vis spectroscopy confirmed AuNP formation, showing a distinct surface plasmon resonance (SPR) peak at 544 nm (Fig.-1D), indicative a well-dispersed and stable nanoparticles. This SPR position is comparable to previous reports using *T. decurrens* (~537 nm).[6,7] The absence of colour change in control samples containing only gold chloride or algal extract confirmed that nanoparticle formation occurred exclusively in this system.

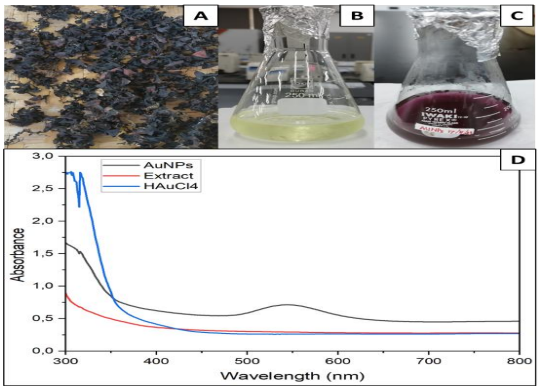

Fig.-1: A. Dry Sample of *Turbinaria decurrens*; B. Mixture Before Reaction; C. Synthesized AuNPs; D. UV–vis Spectra of Synthesized AuNPs, HAuCl4, and *T. decurrens* Extract

Optimised Process for AuNPs Biosynthesis

The UV-vis spectra analysis revealed that precursor-to-extract ratio, temperature, and incubation time critically influenced AuNP synthesis by modulating Au^{3+} reduction, colour shift and SPR peak (Fig.-2). Using 1 mM $HAuCl_4$, AuNPs were synthesized at precursor-to-extract ratios ranging from 2:8 to 8:2. Increasing the precursor proportion intensified and red-shifted the SPR band at 25°C (Fig.-2A) and 37°C (Fig.-2B), whereas this trend was maintained at 50°C (Fig.-2C). At an equivalent ratio (5:5), synthesis at

37°C produced a stronger and narrower SPR band than at 25°C, indicating more efficient nanoparticle formation. In contrast, elevated temperature (50°C) induced rapid SPR red-shifting, band broadening, and colour changes from wine to light purple or colourless at higher precursor ratios, consistent with nanoparticle ratio and instability. The most stable AuNPs were obtained at a 1:1 precursor-to-extract ratio and 37°C, yielding a well-defined SPR peak at 549 nm with minimal band broadening, indicative of uniform size and morphology. SPR intensity increased during the reaction and completed after 60 min (Fig.-2D), marking completion of nanoparticle formation.[8-12] Accordingly, a precursor-to-extract ratio at 37°C for 60 min was identified as the optimal condition for AuNP synthesis using *T. decurrens* extract. The synthesis conditions support SDG 12 (Responsible Consumption and Production) by optimising precursor utilisation and reducing chemical waste, thereby enhancing the sustainability of production.

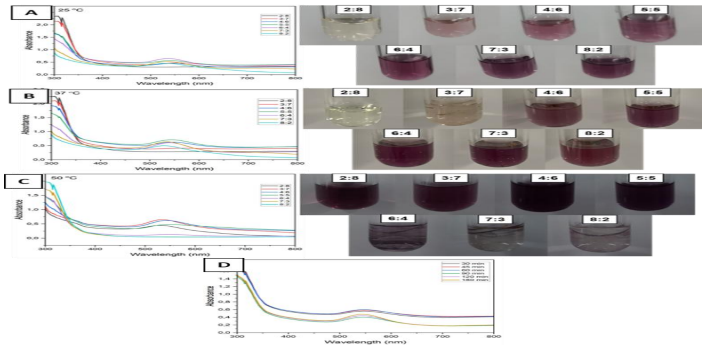

Fig.-2: Panels (A), (B), and (C) Illustrate The UV-vis Absorption Spectra and Corresponding Visual Color Transitions of the AuNPs synthesized at Temperatures of 25°C, 37°C, and 50°C, respectively. Panel (D) Displays The UV-vis Spectral Data Recorded Over Different Incubation Periods Under Optimized Experimental Parameters

Characteristics of Gold Nanoparticles

FTIR Spectra, Particle Size, and Zeta Potential of AuNPs

FTIR spectroscopy revealed that biomolecules in the *T. decurrens* extract acted as reducing and stabilizing agents during AuNP formation (Fig.-3A-B). Characteristic bands at 3392 cm^{-1} (hydroxylic group/polyphenols), 2926 cm^{-1} (C-H stretching/aliphatic), 1596 cm^{-1} and 1255 cm^{-1} (-NH bending and C-OH vibration/polyphenol), and 1031 cm^{-1} (C-O groups/carboxylic acid, phenol, ester) indicate the presence of polyphenols, saccharides, alcohol, and carboxylic acids. The preservation of the spectral profile with increased intensity, together with the appearance of new bands at 3392.77 cm^{-1}, 1101.65 cm^{-1}, and 1124.64 cm^{-1} in the AuNP spectrum, suggests strong interaction between AuNP surfaces and algal biomolecules, consistent with green synthesis mechanisms and previous reports.[7,13] Particle size analyzer (PSA) showed that the biosynthesized AuNPs had a mean hydrodynamic diameter of 45.4 nm (Fig.-3C), while zeta potential measurement yielded a value of −3.8 mV (Fig.-3D), indicating nanoscale dimensions and moderate colloidal stability.[14-16]

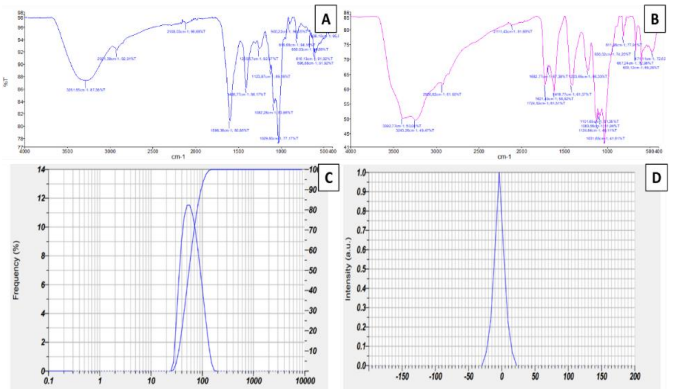

Fig.-3: (A) FTIR Spectra of *Turbinaria decurrens* Algal Extract; (B) FTIR Spectra of AuNPs; (C) Hydrodynamic Particle Size; and (D) Zeta Potential Value of AuNPs

Morphology and X-ray Diffraction of AuNPs

Transmission Electron Microscopy (TEM) analysis showed that biosynthesized AuNPs had an average diameter of 11.5 nm, with a size range from 5.7 nm to 19.4 nm (Fig.-4A-B). The nanoparticles were predominantly spherical, with a minor population of triangular, truncated triangular, rod-like, and irregular morphologies, reflecting heterogeneous growth typical of biogenic synthesis routes.[7,11] X-ray Diffraction (XRD) confirmed the crystalline structure of the AuNPs (Fig.-4C), revealing characteristic diffraction peaks at 2Ø = 38.12, 44.31, 64.42, and 78.57, corresponding to (111), (200), (220), and (311) planes of face-centred cubic metal gold (Au^0).[7]

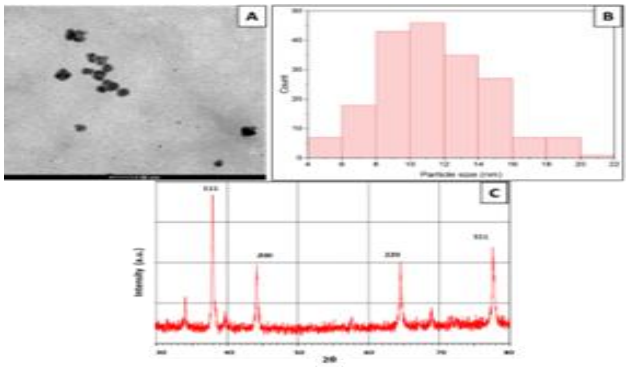

Fig.-4: (A) TEM Micrographs Featuring a 50 nm Scale Bar; (B) Particle Sizes for the Synthesized AuNPs; (C) The X-ray of the Resulting Gold Nanoparticles

Antibacterial and Anticancer Activities of Synthesized AuNPs

The biosynthesized AuNPs exhibited broad-spectrum antibacterial properties against examined pathogens (Fig.-5A). The largest inhibition zones were observed against *Bacillus subtilis* (14 mm) and *Escherichia coli* (13 mm), followed by *Mycobacterium smegmatis* (11 mm) and *Staphylococcus aureus* (10 mm). The negative control showed no activity, whereas ampicillin (20 µg) effectively inhibited all strains. The antibacterial efficacy is consistent with reported size-dependent, multitarget mechanisms of AuNPs, including membrane disruption and inhibition of essential metabolic processes.[16 ,17-18] Cytotoxic against MCF-7 breast cancer cells assessed by MTT assay, showed a dose-dependent reduction in cell viability over the concentration range (8- 512 µg/mL) (Fig.-5B), supporting the intrinsic anticancer potential of AuNPs via mechanisms such as oxidative stress, mitochondrial dysfunction, and apoptosis induction.[19,20] The significant potential of AuNPs in both cancer therapy and diagnostics is widely recognized. They have been successfully utilized in treating various cancers, including breast, lung, cervical, liver, colorectal, and ovarian cancer.[21,22] These findings highlight the therapeutic potential of *T. decurrens*-derived AuNPs, while emphasizing the need for further evaluation of their selectivity and biosafety.[20,23-25] These results align with SDG 3 (Good Health and Well-Being) by contributing to the development of effective antibacterial and anticancer agents to address major global health challenges.

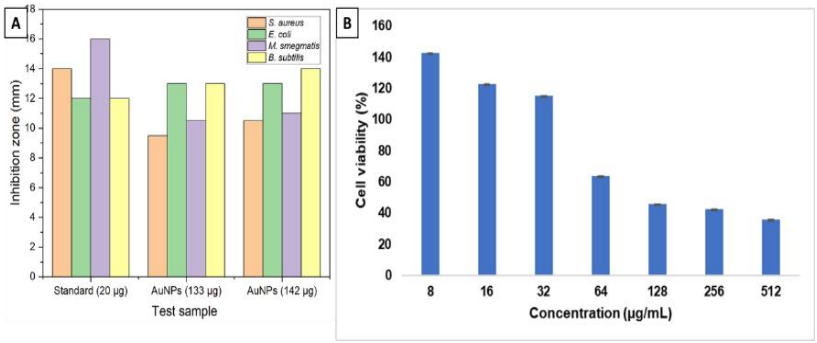

Fig.-5: Application of Synthesized AuNPs for Antibacterial and Anticancer Purposes.
(A) Antibacterial Activity by the Well Diffusion Method Using 133 and 142 µg of AuNPs. (B) Anticancer Activities of AuNPs on MCF-7 Cell Lines

CONCLUSION

This work confirms the effective green synthesis of AuNPs using *T. decurrens* extract as both reducing and capping agents, yielding stable nanoparticles with a shelf life exceeding three months. The resulting AuNPs exhibited diverse morphologies with sizes ranging from 5.7 to 19.4 nm and showed effective antibacterial activity against human pathogens, as well as dose-dependent cytotoxicity toward MCF-7 breast cancer cells. These findings highlight the potential of *T. decurrens*–derived AuNPs for pharmaceutical and biomedical applications. This work supports SDG-3 (Good Health and Well-Being) by advancing novel antibacterial and anticancer agents and aligns with SDG-12 (Responsible Consumption and Production) through eco-friendly synthesis using renewable biomass, reduced chemical use, and minimized waste, highlighting the potential of sustainable nanotechnology for healthcare.

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CONFLICT OF INTERESTS

No conflicts of interest were declared by the authors.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-12: Responsible Consumption and Production*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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