# A Simple Green Synthesis of Aurum Nanoparticles from Seaweeds Produces Impressive Pharmacological Activity

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**Abstract:** This study meticulously investigates the synthesis and pharmacological evaluation of gold nanoparticles (Au NPs) utilizing a green extraction method derived from the brown seaweed, Turbinaria conoides. The goal is to explore eco-friendly approaches for nanoparticle production while assessing their therapeutic potential. Nanoparticles synthesized were characterized using advanced analytical techniques. These techniques provided valuable insights into the nanoparticles' structural, optical, and morphological properties. FTIR identified functional groups, UV-visible spectroscopy examined optical properties, XRD confirmed crystalline structure, and SEM and TEM provided detailed images of particle size and shape. The resulting gold nanoparticles are predominantly spherical, exhibiting a uniform size distribution ranging from 20 to 45 nm, which is ideal for biomedical applications. The cytotoxicity of biologically synthesized gold nanoparticles (AuNPs) was tested on the HepG2 human liver cancer cell line. The results also indicated that Au NPs induced apoptosis in a significant percentage of the cells. This suggests that these nanoparticles could be developed as a promising therapeutic agent for cancer treatment. Further studies are needed to explore their mechanism of action and potential clinical applications. The findings presented in this study indicate a noteworthy foundation for future investigations, highlighting the potential of using eco-friendly synthesized nanoparticles in cancer therapy.

**Keywords**: Turbinaria Conoides, Gold NPs, Antibacterial, MTT-HepG2, liver cancer activity

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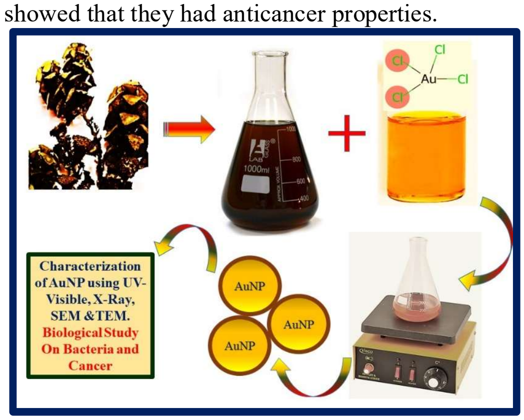
## 1. Introduction

Nanotechnology ranks among contemporary material science's most rapidly advancing sectors, carrying significant implications across various disciplines, including physics, chemistry, and biology. The top-down approach involves breaking down larger materials into smaller components, while the bottom-up approach assembles these particles atom by atom. Both methods are essential for creating nanostructures with unique properties, which can be applied in fields like medicine, electronics, and energy storage. The evolution of nanotechnology has led to a remarkable increase in the manufacturing of nanoparticles, nanowires, and nanotubes utilized in diverse applications. Recent progress in nanotechnology is generating considerable enthusiasm within the life sciences field, especially regarding biomedical devices and biotechnology. Given the depletion of terrestrial resources, researchers are increasingly turning to the oceans for solutions. Over 70 percent of the Earth's surface is encompassed by oceans, which host more than 300,000 species of plants and wildlife. This includes a vast array of organisms, from microscopic plankton to the largest whales. The ocean's biodiversity is crucial for maintaining the health of marine ecosystems, which in turn support life on Earth. Protecting these habitats is essential for the survival of countless species, including humans. In recent years, numerous bioactive compounds have been extracted from marine plants, animals, and organisms.

Thallophyte refers to a group within the plant kingdom that encompasses multicellular marine macroalgae commonly known as seaweed. Although they do not possess true roots and recognizable stems or leaves, seaweeds are non-flowering plants that hold significant ecological and economic importance in marine habitats. These plants are found in diverse environments such as coral reefs, estuaries, rocky shorelines, lagoons, mudflats, sand, shells, pebbles, and mud. The three primary classifications of seaweeds, distinguished by their shape, pigments, structural characteristics, and stored food substances, are Chlorophyceae (green seaweeds), Turbinariaconoides (brown seaweeds), and Rhodophyceae (red seaweeds) [3]. As marine organisms, seaweeds utilize solar energy to transform carbon dioxide and water into sugars. In India, the pharmaceutical potential of seaweeds remains largely untapped, as they are predominantly utilized by industries for extracting phycocolloids. The compounds present in seaweeds demonstrate a broad spectrum of intriguing biological activities, making them an important source of protein, iodine, vitamins, minerals, and polyphenols. In recent decades, seaweeds and their extracts have garnered significant interest from the pharmaceutical sector, recognized as promising new sources of bioactive compounds. Macroalgae have been identified to contain various substances with antibacterial, antiviral, and anticancer properties. The antibacterial efficacy of synthesized AgNPs derived from marine microalgae has been evaluated [4].

Brown algae from the phylum Phaeophyceae, known as Turbinariaornata (Turner) J. Agardh, 1848, thrives in tropical marine habitats, particularly on rocky surfaces. This species is found in the Indian Ocean and the western and central Pacific's tropical and subtropical regions. Many herbivorous fish and echinoderms eat Turbinaria ornata. Fucoxanthin, terpenes, tannins, flavonoids, phenols, saponins, proteins, sulfated polysaccharides, and fucosterols are only a few of the several chemical components it contains. These compounds exhibit a variety of beneficial biological effects, including antibacterial, anti-diabetic, antioxidant, and anti-cancer properties, among others. Additionally, silver (Ag) and gold have been shown to possess bactericidal, antifungal, antimycotic, and anticancer effects. This has sparked interest in exploring the potential applications of gold nanoparticles in medicine and human health. Drug delivery systems, biological sensors, and healthcare equipment are just a few of the applications for nanoparticles made from silver and gold that have been discovered. The efficacy of antimicrobial, antiviral, and chemotherapy medications is at danger due to the rise of resistant to multiple drugs bacteria and viruses. Nevertheless, there is hope that these nanoparticles could help mitigate this issue. The challenge of discovering anticancer treatments that specifically target and eliminate tumor cells while minimizing harmful side effects remains significant. The toxicity of plant or microbial materials is considered when assessing the presence of antitumor substances. Marine organisms, including sponges, tunicates, and algae, have recently yielded antibacterial and anti-cancer compounds. To evaluate the anticancer potential of crude extracts from various marine species, in vitro cytotoxicity tests on malignant cell cultures have been frequently employed. Numerous potential anti-tumor agents have been identified from marine algae in particular. Over the past four decades, it has been reported in several studies that cytotoxic anti-tumor compounds were extracted from marine life. In this work, we extracted nanoparticles of gold using Turbinaria Conoides, a seaweed, and showed that they had anticancer properties.




**Methodology Scheme**

## 2. Literature Review:

A thorough investigation of the synthesis and characterisation of gold and silver nanoparticles generated from Aspergillus terreus was carried out by Bala Kumaran et al. [15]. Their findings demonstrated that AuNPs exhibit significant antioxidant properties. In vitro cytotoxicity assays revealed that AgNPs effectively targeted breast cancer cells (MCF-7), while AuNPs displayed pronounced cytotoxicity against liver cancer cells (HepG2), instigating apoptosis and cell cycle arrest. Viswanathan et al. [16] successfully synthesized 20 nm-sized eco-friendly gold nanoparticles (Cp-AuNPs) utilizing the red marine algae Champiaparvula. Notably, the Cp-AuNPs exhibited potent anticancer properties against lung cancer cells (A549), indicating their potential for therapeutic application. Palaniappan Pitchaia et al. [17] reported a novel, environmentally benign method for synthesizing gold nanoparticles (AuNPs) from Caulerpa racemosa, a seaweed known as 'sea grapes.' This synthesis involved combining the seaweed extract with chloroauric acid and gentle heating, yielding AuNPs with distinctive spherical and cubic morphologies, measuring between 18.94 to 45.54 nm. With an IC50 value of 25 mg/mL, the produced AuNPs showed strong cytotoxicity toward human lung cancer cells (H460) and noteworthy antibacterial activity, especially against Gram-negative Escherichia coli. These findings make them attractive options for nanotherapeutic oncology applications. Using fucoidan as a stabilizing and reducing agent, Rajeshkumar et al.'s study [19] explores the manufacture and possible uses of gold nanoparticles (AuNPs). The surface analysis verifies a mean size of 31 nm, falling between 21 and 44 nm. One important finding was the discovery of a surface plasmon resonance (SPR) peak at 555 nm, which shows that the AuNPs were successfully synthesized and stabilized. This is important for a number of uses, including as drug administration and sensing. Crucially, the study tested the produced Au NPs' anti-cancer effectiveness against liver cancer cell lines, with encouraging results indicating the possibility of using these nanoparticles in oncological treatment settings. Collectively, this body of research elucidates the successful synthesis, characterization, and prospective biomedical applications of Au NPs paving the way for future explorations in Nanomedicine and biotechnology. It emphasizes the multifaceted roles of biogenic nanoparticles in medicine and nanotechnology, particularly in cancer therapy and ant oxidative applications. However, the researchers underscore the promising therapeutic applications of these nanoparticles, though they advocate for extensive toxicity assessments.

## 3. Research Gap:

Using an extract from the brown seaweed *Turbinaria conoides*, the study provides persuasive results about the production of gold nanoparticles and its apparent cytotoxicity against MDA-MB-231 breast cancer cells. Nevertheless, several notable research gaps merit further exploration. Firstly, while the study suggests cytotoxic effects, it does not provide a comprehensive analysis of the underlying molecular mechanisms responsible for these effects. A thorough understanding of how these nanoparticles induce apoptosis or modulate cellular pathways in cancer cells is essential for evaluating their potential therapeutic applications. Furthermore, although the study references certain characterization techniques for the nanoparticles, a more extensive evaluation—incorporating parameters such as size distribution, surface charge, and stability—is vital for assessing their applicability in biomedical contexts. The research predominantly focuses on in vitro evaluations, which constrains insights into safety, biodistribution, and therapeutic efficacy in more physiologically relevant environments. In this context, in vivo studies utilizing appropriate animal models are necessary to translate laboratory findings into clinical relevance. Clinical trials are also crucial to assess both the safety and efficacy of these nanoparticles in human subjects. A comparative analysis with established cancer treatment modalities would further elucidate the potential advantages and limitations of this approach. Lastly, while the environmental benefits of using seaweed in the synthesis process are acknowledged, a comprehensive evaluation of the sustainability and ecological impact of seaweed sourcing is imperative. Addressing these research gaps will enhance our understanding of the potential applications of biologically synthesized nanoparticles in cancer therapy and facilitate their integration into broader medical and environmental frameworks.

## 4. Materials and Methods

### 4.1 Chemicals required

Sigma-Aldrich supplied the ascorbic acid, $NaBH_4$, 2,2-diphenyl-1-picrylhydrazyl (DPPH), and chloroauric acid ($HAuCl_4.3H_2O$, 99.99%). Fisher Scientific was the supplier of solvents such as acetic anhydride (99%), pyridine (99%), ethanol (99%), and ethyl acetate (99%). Sodium hydroxide (NaOH) 99%, was purchased in analytical grades from Himedia Laboratories and used as received. Milli-Q water was obtained from Pall's bio cascade water system and used for studies.

### 4.2 Sample Collection

The extract was made from brown seaweed called Turbinaria conoides, which was gathered in south Indian coastal areas and air-dried for 48 hours. (Figure 1).

**Figure 1: Turbinaria conoides**

### 4.3 Preparation of Turbinaria conoides extract

To remove waste products, the dried seaweed of the Turbinaria conoides species was rinsed with distilled water. For the synthesis of the seaweed extract, 5 grams of thoroughly cleaned seaweed were placed in a 500 mL Erlenmeyer flask, which was then heated with 100 milliliters of double-distilled water for a duration of 15 minutes. The resulting filtered algae extract was subsequently stored at a temperature of 0°C for future utilization, maintaining its viability for several weeks.

### 4.4 Green gold nanoparticle production

By adding 1 mM of HAuCl4 to a broth medium with a neutral pH that contained 36 ml of extract and 64 ml of distilled water, gold nanoparticle biogenesis was carried out. Throughout the procedure, the solution was kept at a constant 37 °C. Following the reaction, the mixture was centrifuged for 30 minutes at 75,000 RPM, producing a pellet that was then dissolved in distilled water. A Millipore filter with a 0.45 µm pore size was then used to filter this mixture. Gold nanoparticles were produced by calcining the resulting dry compound at 400 °C in a muffle furnace. The resulting nanoparticles were examined using field emission scanning electron microscopy (FE-SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FT-IR), and X-ray diffraction (XRD).

### 4.5 Antibacterial activity

The agar well diffusion method was used to assess the nanoparticles' antibacterial qualities. To nutrient agar plates with 15 mL of solidified material, an overnight culture of Escherichia coli, Pseudomonas aeruginosa, S. aureus, and B. subtilis was added. In particular, each plate received 100 µL of the bacterial culture. A drilling device was then used to produce wells in the agar, which were subsequently filled with samples of nanoparticles and standard solutions. For a whole day, the plates were incubated at 37 °C. The inhibitory zones' sizes were measured in millimeters following the incubation period.

### 4.6 MTT Assay test

The National Centre for Cell Science in Pune, India, provided the HepG2 human liver cancer cells used in this investigation. Roswell Park Memorial Institute (RPMI) medium was supplemented with 10% fetal bovine serum (FBS), 225 µg/ml penicillin/streptomycin, 100 µg/ml gentamicin, and 1 µg/ml amphotericin B while the cell lines were growing in monolayers. The cells were incubated in an environment with high humidity and 5% carbon dioxide at 37°C. The cells were given a full day to reach confluence prior to usage.

### 4.7 Dual staining with ethidium bromide (EB) and acrylidine orange (AO)

Using AO/EB dual labeling, apoptosis was found in cells treated with Au NPs. 25 ml of treated and untreated cell suspension (5*106 cells/ml) was mixed with 1 ml of fluorescent dye and a mainly based bromide dye mix [21]. The resulting solution was promptly observed under a Nikon Ti series inverted fluorescence microscope at a magnification of 10x. It's worth noting that a minimum of 200 cells were observed in each of the five fields used to compute the overall cell count.

## 5. Results and Discussions

An extract made from the brown seaweed T. Conoides was used as a reducing agent in the synthesis of gold nanoparticles. Using a variety of analytical methods, the final gold nanoparticles' dimensions, form, photophysical characteristics, and medicinal uses were verified.

### 5.1 FT-IR spectrum of the Gold nanoparticle.

The Fourier-transform infrared spectroscopy (FT-IR) method was used to analyze the gold nanoparticles contained in the filtrate. There are peak values at 3394, 1628, 1142, 1034, 687, 540, 463, and 432 cm−1 in the AuNp-Tc gold nanoparticles (Figure 2). Both the amide I and amide bonding II sections, which are typical of proteins and enzymes that reduce metal ions for the creation of metal nanoparticles, don't seem to have any peaks. The observed peaks are more indicative of the seaweeds' rich flavanones and terpenoids.

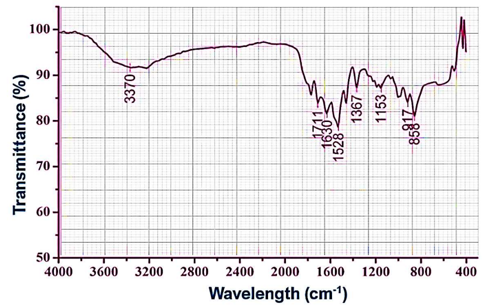



Figure 2: FT-IR image of Gold NPs

### 5.2. UV-Visible Absorption spectrum of the Gold nanoparticle.

1 ml aqueous solution of $HAuCl_4$ was combined with an aqueous extract of T. conoides. After a period of 30 minutes, a distinct pinkish-violet color emerged, indicating the successful biosynthesis of gold nanoparticles (NPs). During this incubation phase, the activation of surface plasmon vibrations enhanced the intensity of the pinkish-violet hue. The discovery of a distinctive absorption peak at 530 nm (see Figure 3) provided additional confirmation of the creation of gold nanoparticles. This peak exhibited stability at the same wavelength for up to one hour, suggesting that the phytoconstituents present effectively stabilized the generated gold NPs.

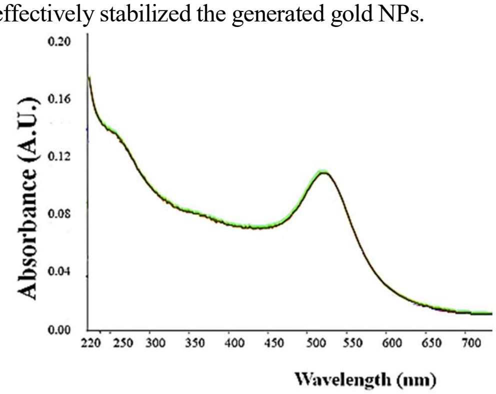



Figure 3: UV-visible image of Gold NPs

### 5.3 Characterization of gold nanoparticles using XRD.

The X-ray diffraction (XRD) pattern of the synthesized gold nanoparticles (AuNPs) is illustrated in Figure 4. Five distinct peak patterns of diffraction are visible at 38.3°, 44.5°, 64.8°, 77.7°, and 81.6° angles. According to JCPDS file no. 04-0784, these peak values correlate to the (111), (200), (220), (311), and (222) Bragg discussions, accordingly, verifying the face-centered cubic, or fcc, arrangement of the colloidal AuNPs.

Remarkably, the (111) plane peak's strength at 38.3° was noticeably higher than the other peaks', indicating that the (111) plane signifies the nanoparticles' primary orientation.

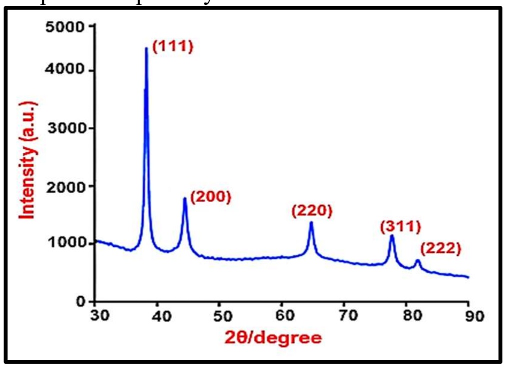



**Figure 4.** XRD of the gold nanoparticles synthesized using *Turbinaria conoides*

**4.5 Characterization of nanoparticles using SEM**

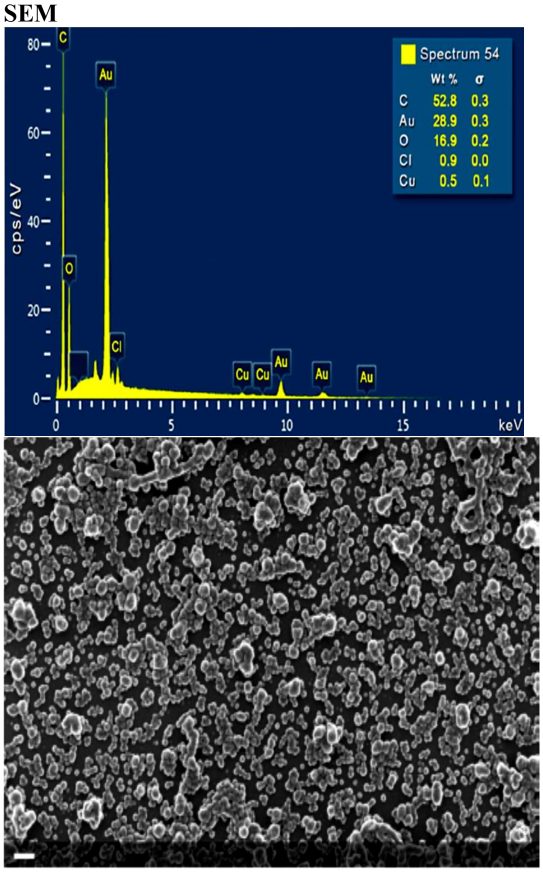



**Figure 5.** SEM micrograph of the gold nanoparticles synthesized using Turbinaria Conoides.

We obtained high-resolution images of the produced gold nanoparticles using scanning electron microscopy (SEM) in order to analyze their shape. In Figure 5, nanoparticles smaller than 50 nm are clearly identifiable. A closer analysis of the SEM imagery reveals a distinct layer of these smaller nanoparticles residing on the surfaces of larger particles. Observations indicate that the majority of the nanoparticles exhibit a spherical morphology, though a variety of non-spherical shapes were also observed. The presence of diverse particle sizes likely correlates with the observed variations in shape.

**4.6. Characterization of gold nanoparticles using TEM**

The uniform distribution of the particles was demonstrated by the transmission electron microscope pictures (Figure 6). Upon analysis of the image, it was determined that the particle size distribution ranged from approximately 20 to 45 nm. This particular distribution, primarily comprising spherical gold nanoparticles with a minor presence of rod-, triangle-, and hexagon-shaped nanoparticles, was identified as a hallmark of gold. At the nanoscale, gold has been demonstrated to exhibit a finely divided structure with a diameter of 43 nanometers.

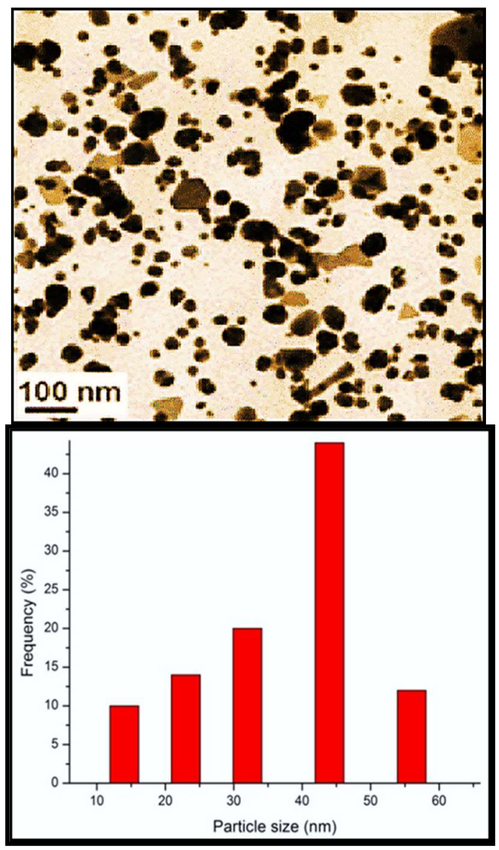



**Figure 6.** TEM micrograph of the gold nanoparticles and the particle size distribution

**4.7. Antibacterial activity of gold nanoparticles**

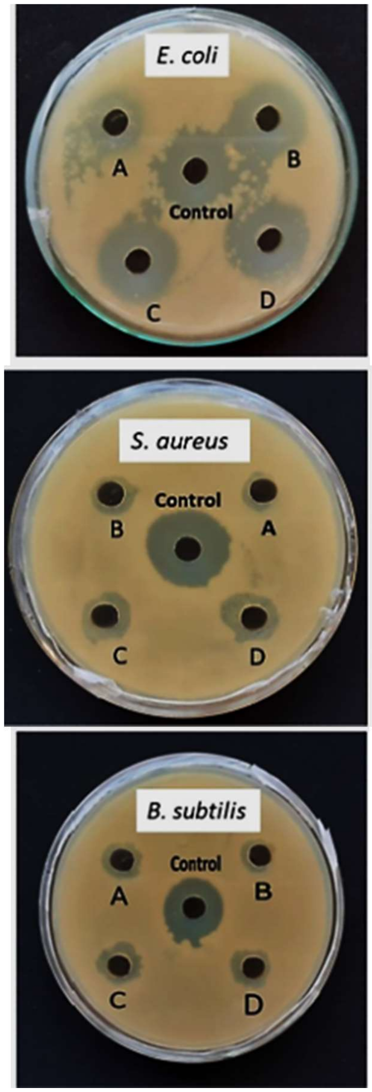



Figure 7. Antibacterial efficiency of gold nanoparticles

The antibacterial properties of the extracts and the produced nanoparticles were assessed using the agar-mediated dissemination methodology. Since it is widely acknowledged that gold nanostructures (AuNPs) possess potent antimicrobial qualities, the antibacterial efficacy of AuNPs was assessed against a number of bacteria: Together with the gram-negative ones' strains of Escherichia coli and the bacterium Pseudomonas there are also the Gram-positive strains of the genera Staphylococcus aureus and bacteria such as Bacillus subtilis (Figure 7).

**Table 3. Antibacterial efficiency of gold nanoparticles**

| **Sample used** | **Zone of inhibition in mm for different bacteria** | | | |
|---|---|---|---|---|
| | ***E.coli*** | ***B.subtilis*** | ***P.aeruginosa*** | ***S.aureus*** |
| Extract | 2 | Nil | 1mm | 2 mm |
| Nanoparticle | 11 | 9mm | 13 mm | 12mm |
| DMSO | Nil | Nil | Nil | Nil |
| Disc | 4 | 3 mm | Nil | 3mm |

According to our research, gold nanoparticles had the strongest bactericidal action, particularly against the bacteria P. aeruginosa and E. coli. They were followed by B. subtilis and S. aureus (Table 3). Both Gram-positive and Gram-negative bacteria differ in the chemical composition of the membranes that cover their cells, which may be the cause of these differences [26]. Therefore, a unique compound that operates through a different mechanism against pathogens could provide an alternative option for treating bacterial infections.

**4.8. MTT viability test**

The study evaluated the toxicity and viability of HepG2 human liver cancer cells in response to varying concentrations of gold nanoparticles (AuNps) and seaweed extract, ranging from 1 to 100 mg/ml. The seaweed extract from T. conoides, which was employed as a positive control, and cells treated with $HAuCl_4$ showed negligible negative effects up to 100 µg/ml, the tested concentration range. Interestingly, a lower $IC_{50}$ value of 32 µg/ml indicates a greater potential for cell growth inhibition. However, a significant 77% of the treated cells showed indications of cytotoxicity caused by the gold nanoparticles at a dosage of 50 µg/ml. These findings indicate that the cytotoxicity of ecologically synthesized gold nanoparticles is amplified at higher concentrations.

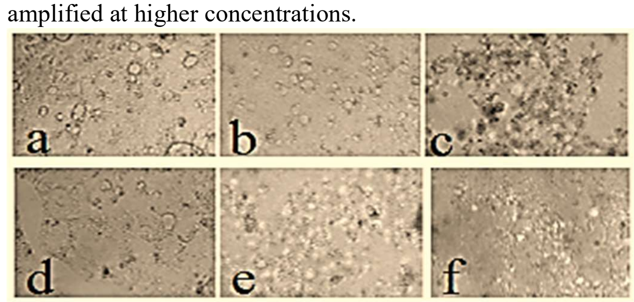



**Figure 8**. MTT assay AuNPs on HepG2 human liver cancer cell lines

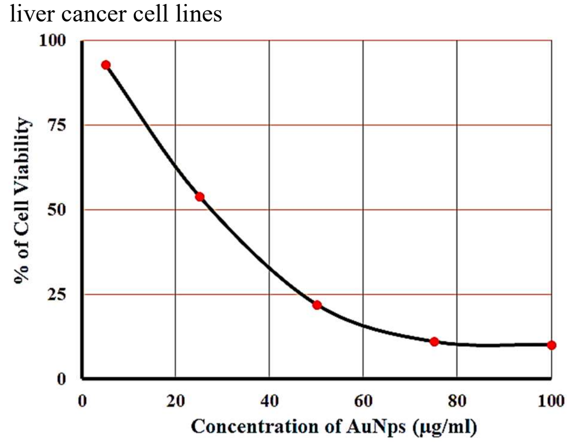


**Figure 9.** IC50 graph of AuNps on HepG2 human liver cancer cell lines

### 4.9. Dual labeling for apoptosis (AO/EB)

After carefully plating HepG2 human liver cancer cells in 48-well culture plates, they were incubated at 37 °C in a humidified environment with 5% $CO_2$. Following this, the cells were treated with varying concentrations of gold nanoparticles (AuNps) at 10, 25, 50, 75, and 100 µg/ml for a duration of 24 hours, based on the calculated IC50 value of 32 µg/ml. Subsequently, a 100 µl aliquot of a dual fluorescent dye mixture comprising ethidium bromide and acridine orange in a 1:1 ratio was added to both the control and AuNps-treated cells. Observations were made using a Nikon Ti series inverted fluorescence microscope at 10x magnification, ensuring that at least 200 cells were counted across five randomly selected fields for analysis. This dual-labeling approach aimed to elucidate the morphological changes indicative of apoptosis. During microscopy, viable cells exhibited blue fluorescence, whereas both early and late apoptotic cells displayed characteristic features of apoptosis. Nonviable cells were distinctly identified based on their staining profiles. Significant morphological changes, such as condensed nuclei, membrane blebbing, and the development of apoptotic bodies, were notably brought about by the application of gold nanoparticles. On the other hand, the nuclear structure of control cells remained normal. Furthermore, in comparison to cells exposed to the gold nanoparticles, cells treated with HAuCl4 showed less apoptotic bodies.

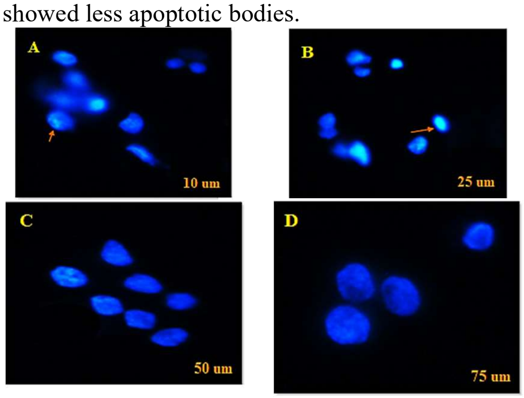



Figure 10. Fluorescent microscope images upon staining with AO and EtBr and 10 to 75µg/ml of AuNP-treated with hepG2 cells.

**6. Discussion:** Recent studies have indicated that gold (Au) nanomaterials can be synthesized through the rapid degradation of chloroaurate ions using extracts obtained from seaweed. Proteins, phenols, and flavonoids are among the biological substances that are naturally found in seaweed and are used in this procedure. These substances are crucial for the stabilization of nanomaterials and for the decrease of metal ions. High-resolution scanning electron microscope (HR-SEM) and transmission electron microscopy (TEM), respectively, were used to validate this the process of biosynthesis The results showed that the generated gold nanoparticles (AuNPs) were uniformly sized and primarily spherical, with a size range of 20 to 45 nanometers. Moreover, strong correlations found in X-ray diffraction (XRD) spectra verified the occurrence of crystalline face-centered cubic gold in the biosynthesized AuNPs. Notably, this biogenic method for nanoparticle production has a significantly lower environmental impact compared to traditional physical, chemical, or microbial approaches, making it a promising alternative. An interesting finding from the research is the enhanced antibacterial efficacy of these nanoparticles, which has sparked substantial interest in the use of seaweed extracts for gold nanoparticle biosynthesis. While the reduction of metal salts via this method is environmentally friendly, it is also a complex molecular process that relies on a diverse array of seaweed components, including minerals, enzymes, proteins, citrates, amino acids, and polysaccharides. The investigation also showed that AuNPs dramatically and dose-dependently decreased the ability to survive of HepG2 cells, a type of cell used to study liver cancer. In particular, cytotoxicity increased as you increased gold nanoparticle concentrations; dosages of 32 and 75 µg/mL caused 77% and 90% cell death, correspondingly. This implies that targeted cells and the dimensions of nanoparticles are closely related to their cell death, which is consistent with observations from various other studies. Overall, this research underscores the therapeutic potential of green gold nanoparticles as compared to those synthesized through chemical methods, highlighting the need for further exploration of biosynthesized nanoparticles as a potential source for novel cancer treatments.

### 6. Future scope:

This study shows the strong potential of gold nanoparticles made using Turbinaria Conoides seaweed extract. These nanoparticles can help fight HepG2 human liver cancer cells. The research highlights how these nanoparticles can kill cancer cells, make them self-destruct (a process called apoptosis), and specifically target cancer without harming healthy cells. However, there are still important areas to explore for further progress. While laboratory studies are helpful, we need to test these nanoparticles in living animals to see how they really work. It's essential to study their effects not just on cancer cells but also on harmful bacteria, viruses, and fungi. We also need to understand how they cause cancer cells to die at a deeper level for their use in real cancer treatment. Future research should include studies with animals to check how safe they are, how they spread in the body, and how effective they are in a more realistic setting. Conducting clinical trials with human patients will be crucial to determine their safety and effectiveness for breast cancer treatment. We should also compare these nanoparticles with current cancer treatments to see how they measure up, including their benefits and limitations. Lastly, we must consider the environmental impact of using seaweed for making these nanoparticles to ensure this method is good for nature. While this study provides a strong base for using gold nanoparticles from seaweed for cancer treatment, filling these research gaps is necessary to turn these findings into successful treatments for people.

## 7. Conclusions.

In conclusion, gold nanoparticles synthesized from Turbinaria conoides extract demonstrate significant potential as anticancer agents. These nanoparticles are produced through a rapid and environmentally friendly process, exhibiting marked cytotoxicity against HepG2 human liver cancer cells, with the most pronounced effects observed at an IC50 dosage of 32 µg/ml. This suggests that the effect on cell viability is influenced by concentration. Additional research on how they work of action suggests that these gold nanoparticles cause cells with cancer to undergo apoptosis. Numerous anatomical alterations, such as the presence of membrane blebbing, condensed nuclei, and apoptotic bodies, support this. These results highlight the ability of these nanoparticles to target and destroy tumor cells specifically while avoiding inflammatory reactions. Recognizing current research gaps is crucial, though. Even though this work provides encouraging new information, more investigation is required to completely understand the molecular processes behind these nanoparticles' harmful effects. Furthermore, the eco-friendly synthesis method and sustainable sourcing of seaweed suggest that these biologically synthesized nanoparticles not only hold promise for cancer treatment but also align with environmental sustainability principles. This comprehensive approach to biomedical research highlights the capacity of biogenic nanoparticles to contribute both to healthcare advancements and to responsible environmental practices. Because of strong apoptosis qualities, selective toxicity to cells, and environmentally friendly manufacturing processes, these ecologically produced gold nanoparticles thus offer a viable path toward the creation of novel cancer treatments.

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