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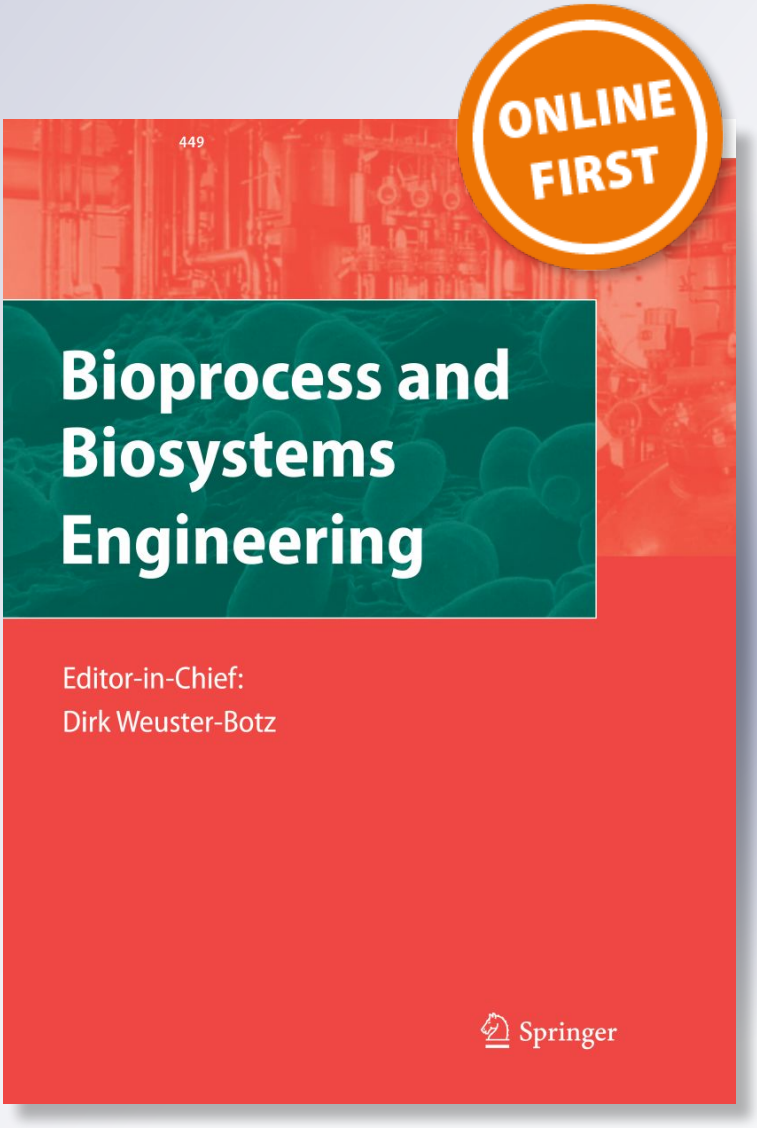

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CRITICAL REVIEW

Recent progress of algae and blue–green algae-assisted synthesis of gold nanoparticles for various applications

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Abstract
The hazardous effects of current nanoparticle synthesis methods have steered researchers to focus on the development of newer environmentally friendly and green methods for synthesizing nanoparticles using nontoxic chemicals. The development of environmentally friendly methods of nanoparticle synthesis with different sizes and shapes is one of the pressing challenges for the current nanotechnology. Several novel green approaches for the synthesis of AuNPs have been explored using different natural sources, such as plants, algae, bacteria, and fungi. Among organisms, algae and blue–green algae are of particular interest for nanoparticle synthesis. Gold nanoparticles (AuNPs) have a range of applications in medicine, diagnostics, catalysis, and sensors because of their significant key roles in important fields. AuNPs have attracted a significant interest for use in a variety of applications. The widespread use of AuNPs can be accredited to a combination of optical, physical, and chemical properties as well as the miscellany of size, shape, and surface composition that has been adopted through green synthesis methods.

Keywords Gold nanoparticles · AuNPs · Algae · Blue–green algae · Green synthesis · Environment friendly methods

Introduction

Nanotechnology is an interdisciplinary science with great potential in revolutionizing the science and industrial technologies. The word nanotechnology is generally used when referring to materials, 0.1–100 nm in size. When a material is reduced to the nano size, it acts differently and exhibits some new properties, which are completely lacking in its macroscale or bulk form. Nanoparticles are of great scientific interest, because they bridge the gap between bulk materials and atomic and/or molecular structures [1–4].

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Nanoparticle synthesis, particularly in the biological field, have a range of applications, such as biomolecular detection and diagnostics, therapeutics, catalysis, microelectronic, DNA sequencing, pharmaceuticals, photonics, optics and optoelectronics, sensors, and nanocomposites [2–6].

When 1 g of gold is converted to nanoscale particles, the particles can cover an area of 100 km^2. Gold nanoparticles (AuNPs), 2.5 nm in size, melt at much lower temperatures (~ 300 °C) than bulk gold (1064 °C) [2]. The synthesis, properties, and application of gold clusters, colloids, and nanoparticles have been reported. The interest in AuNPs has increased rapidly over the past few years because of their intriguing properties, such as strong surface plasmon, catalytic, redox behavior, and applications in medicinal diagnostics, imaging, optical, and forensic areas [1–5].

Synthesis of AuNPs

A large number of methods have been used in the synthesis of AuNPs, including physical and chemical techniques, with the aid of an external energy supply, such as photoirradiation, ultrasound irradiation, heating, and precipitation–deposition, as well as co-precipitation, although most

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of these methods have successfully produced pure and well-defined nanoparticles, but these methods are comparatively expensive and quite hazardous to the environment. Therefore, researchers are now concentrating on the development of clean and green AuNPs synthesis methods to prevent their adverse effects on the environment. A number of bio mimic processes, such as those employing plants, algae, fungi, bacteria, and yeast, have been used for the low-cost, energy-efficient, and nontoxic production of AuNPs [4–6].

Typically, AuNPs are obtained by the chemical reduction of tetrachloroauric acid by sodium citrate or $NaBH_4$. On the other hand, these approaches are based on the use of external chemical reductants, which often produce undesirable side products and contaminate the nanoparticles. Therefore, a series of functionalizing agents for AuNPs that display a dual role as an effective reducing agent for the gold precursor and stabilizers by providing a capping to the metal nanoparticles have recently been developed [6].

Methods used to synthesize AuNPs

Nanomaterials are generally classified into many categories, such as metal oxides, carbonaceous nanomaterials, nanopolymers, semiconducting nanomaterials, metal nanoparticles, and few others, as shown in Fig. 1.

Nanoparticles such as metal nanoparticles, metal oxide, and semiconductors nanoparticles are generally produced by the top–down approach of bulk materials and later treating with reagents and heating. Noble metal nanoparticles, TiO_2, and ZnO are used widely in applications, such as skin care products, coatings, and photocatalysis, owing to their ultraviolet light blocking and harvesting properties [3–8]. Carbonaceous nanomaterials are used in fullerenes, graphene, and single- and multi-walled nanotubes [9]. Single-walled nanotubes are used in some industries because of their high strength-to-weight ratios, which are 460 times greater than steel [10]. Nanopolymers have a variety of various composition and properties that depend on the size, topology, flexibility, and controlled molecular weight. These materials include macrocapsules, nanolatex, colored glasses, chemical sensors, modified electrodes, DNA-transfecting agents, and therapeutic agents for prion diseases, hydrogels, and DNA chips [7–10].

Applications of AuNPs

These materials are also beneficial in medical imaging [9–11]. Gold is a precious, biocompatible metal, and colloidal gold has been used as a drinkable solution since ancient times for its curative properties for various diseases [12]. AuNPs have many applications (Fig. 2), including medical imaging, cancer therapy, electronics manufacturing, catalysts, and biosensor technology [13–17]. AuNPs have been incorporated into carbon nanotubes and established transistors used in DNA detection, which has resulted in an increase in DNA detection in the femto molar range [18]. AuNPs have been used in vivo sensors that increase the blood flow to specific areas [19]. AuNPs are also helpful in treatments for serious human diseases, such as HIV [20]. With this interest, 2 nm mercapto benzoic acids have been reported to enhance the quality of AuNPs and provide a route to the fabrication of multivalent therapeutics used to prevent the binding of the HIV-1 virus to human T cells. AuNPs–peptide complexes are produced to facilitate drug delivery to the cell nuclei as well as other potential uses [21]. AuNPs also show optical properties and have been assessed for applications to microscale mirrors for use in high end optical displays [22]. The novel properties and high performance of AuNPs are dependent on the particle size and uniform size distribution [23]. One of the promising applications of AuNPs is in the area of catalysis, and AuNPs can act as excellent catalysts for many organic reactions. These unique properties of AuNPs have prompted many studies on the catalytic efficiency of AuNPs. Aromatic nitro compounds are one of the most commonly used chemical groups in the manufacturing industry but are extremely hazardous if released into

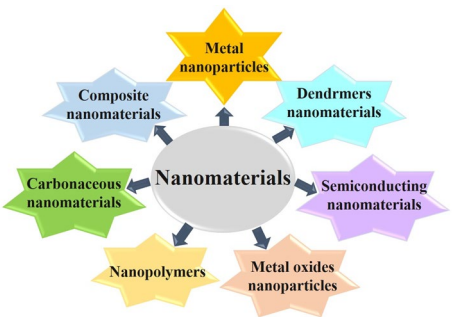

Fig. 1 Types of nanomaterials

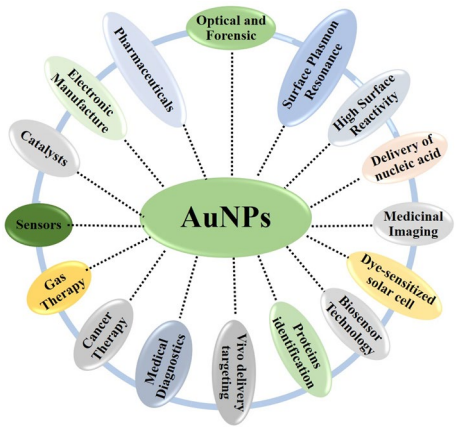

Fig. 2 Various applications of AuNPs

the environment. On the other hand, the reduced products of these aromatic nitro compounds are largely used in the preparation of polymers, rubber products, and hair dyes, as intermediates for drugs in the pharmaceutical industry, etc. [24]. The uses of AuNPs can be attributed to the unique physical properties of gold (i.e., density, conductivity, stability, etc.) and the variety of sizes, shapes, and surface compositions that can be achieved through the synthesis of AuNPs [21]. With continued interest, the different surface chemistry compositions of AuNPs can be synthesized in a variety of processes with different shapes, including spheres, cubes, rods, and nanowires [25].

AuNPs have been used in spectroscopic analysis to determine their surface plasmon resonance (SPR) properties; their colloids exhibited a range of colors ranging from red, purple to violet with increasing particle size. The color varies with the strong and scattering of radiation at 520 nm, which imparts collective oscillation to the conduction electrons on the surface of the AuNPs when excited with incident light [26]. The SPR properties of AuNPs depend on the particle size, shape, protective ligands, refractive index of the solvent, and temperature. AuNPs can also enhance Raman radiation scattering, which leads to surface-enhanced spectroscopy (SERS)-based sensing. AuNPs also enhance or quench the fluorescence of a fluorophore depending on the AuNPs–fluorophore distance. A fluorophore (or fluorochrome, similar to a chromophore) is a fluorescent chemical compound that can re-emit light upon light excitation. Fluorophores typically contain several combined aromatic groups, or planar or cyclic molecules with several π bonds [27]. Despite this, there is variety of AuNPs syntheses (Fig. 3), but there are many problems, such as the use of toxic solvents, generation of hazardous by-products, and high-energy consumption [28]. On the other hand, other ways for producing metallic nanoparticles synthesis involve the use of natural resources, which is a cost-effective and environmentally friendly approach [29].

Simple prokaryotes to complex eukaryotic organisms, including higher angiospermic plants, are being used for the production of low-cost and nontoxic metallic nanoparticles [30]. This has prompted interest towards the use of plants as a natural resource in the phytosynthesis of metallic nanoparticles. In addition, plant polyphenols, proteins, carbohydrates, and other biomolecules are used as reducing and stabilizing agents in nanoparticle synthesis [3, 4, 31, 32].

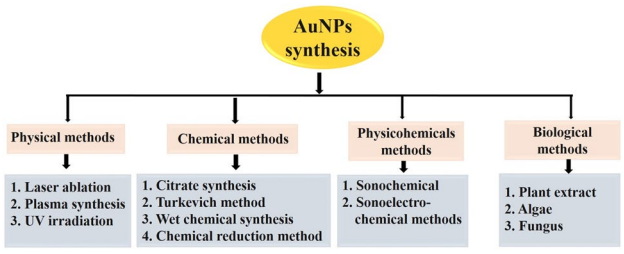

Fig. 3 Different methods used to synthesize AuNPs

Therefore, macroalgae have attracted attention in research for AuNPs' biosynthesis, because they are a natural resource and have tendency to reduce and stabilize AuNPs. Marine macroalgae are considered biofactories because of the highly rich source of biological active compounds and antioxidants, such as polyphenols, bromophenols, polysaccharides, photosynthetic pigments, proteins, vitamins, fatty acids, glycolipids, and protective enzymes [33]. Macroalgae, like other photosynthesizing organisms, can produce free radicals and other oxidizing agents. Their structural components are resilient to oxidative damage. The chemical composition of macroalgae act as reducing and stabilizing agents in nanoparticle synthesis similar to plants. The use of macroalgae extracts gives an eco-friendly and a cost-effective new approach to the synthesis of metallic nanoparticles [33, 34].

Morphologies (shapes and sizes) of AuNPs

Figure 4 represents TEM images showing the different shapes and sizes of AuNPs synthesized from various microorganisms: (a) Au nanoplates [35], (b) spherical, triangular, and hexagonal-shaped AuNPs [36], (c) spherical AuNPs [37], (d) spherical and triangular AuNPs [38], (e) oval-shaped AuNPs [39], (f) AuNPs in the presence of a live cell filtrate [40], (g) hexagonal and triangular Au crystals [40], and (h) membrane bound AuNPs [41].

The use of eco-friendly materials, such as bacteria, fungi, and algae, for the synthesis AuNPs have been promoted as a more environmentally friendly approach compared to the chemical approach. This synthesis procedure is expected to have biomedical applications, because no toxic compounds are used in the process [42]. As part of an ongoing study of AuNPs by algae, the literature survey showed that marine plants, microorganisms, and algae are sources for AuNPs synthesis. Seaweeds or benthic marine algae are a group of plants found in marine or brackish water. The biosynthesis of AuNPs using marine algae is as an eco-friendly approach [43] that produces AuNPs with medical, pharmaceutical, diagnostics, and sensor applications.

On the other hand, the chemical synthesis of AuNPs produces synthetic materials that are toxic and not beneficial to the environment. In this regard, the utilization of naturally occurring materials, such as fucoidans, to produce a clean and simple synthesis of AuNPs has attracted considerable interest. Fucoidans contain sulphated polysaccharides and are found in marine algae *Cladosiphon okamuranus* and *Kjellamaniella crassifolia*. The appropriate conditions for synthesis were examined to obtain the nanometer-sized AuNPs. The synthesized AuNPs were characterized by spectroscopy to determine the size, morphology, and SPR. The

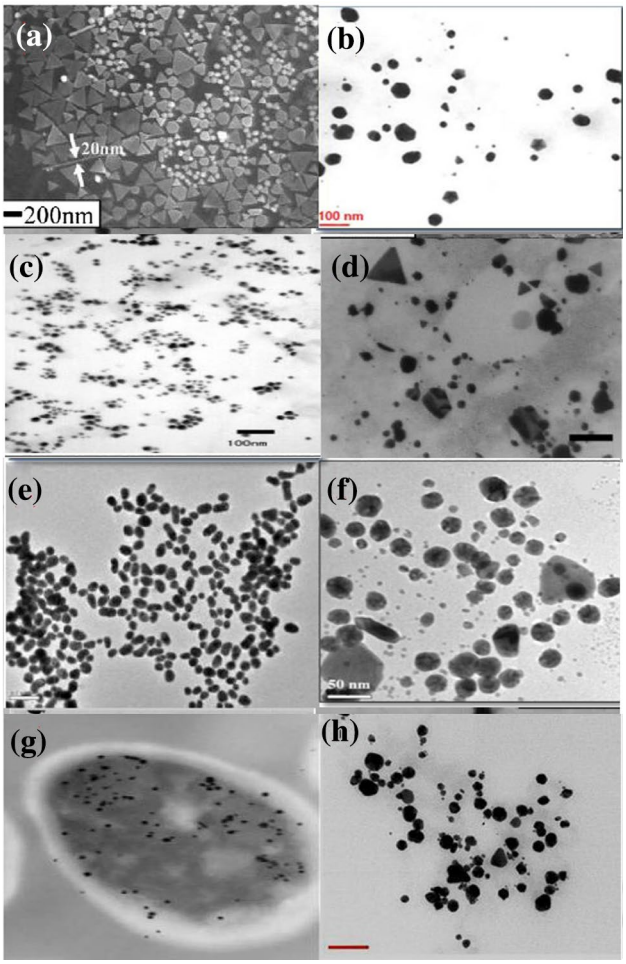

Fig. 4 Different types and morphologies of AuNPs [35–41]

spectral evidence revealed fucoidan-stabilized AuNPs with the optimal number of gold atoms-to-fucoidan weight ratio with a spherical shape, 8–10 nm in size, and the absorption maxima of the SPR band was observed at approximately 527–530 nm. AuNPs stabilized by o-fucoidan, which has a linear polymer structure, were more monodisperse than those stabilized by t-fucoidan which has a branch polymer structure. Therefore, fucoidan can be employed solely for AuNPs' synthesis, and the sulfate constituents in fucoidan are important for the stabilization of AuNPs which would be attractive for applications in metallic nanoparticle synthesis [44].

Biosynthesis of AuNPs using several algae and blue–green algae

Algae are naturally occurring plants that include diverse organisms ranging from unicellular genera, such as *Chlorella*, and the diatoms to multicellular forms, such as the giant kelps, a large brown alga that can grow up to 50 m in length. Most algae are aquatic and autotrophic, and lack many of the distinct cell and tissue types found in land plants, such as stomata, xylem, and phloem. The largest and most complex marine algae are called seaweeds. Algae are a source for the production of metallic nanoparticles. Examples for the synthesis of AuNPs using the extract of algae include *Sargassum wightii* [45], *Turbinaria conoides* [46], *Laminaria japonica* [47], and *Stoechospermum marginatum* [48].

This review article covers the green and biosynthesis of AuNPs using several algae and blue–green algae (Tables 1, 2) and assesses their biological potential applications. Algae have advantages over other microorganisms, such as high tolerance against harsh environmental conditions. The algae-assisted synthesis of AuNPs is economical and environmentally friendly, because the synthesis takes place in water under normal condition and no any toxic chemicals are involved in the synthesis. The biological potential applications of the biosynthesized AuNPs have also been discussed. Applications of environmentally friendly AuNPs in various fields have made them popular and applicable. The biogenic synthesis of AuNPs using algae is a simple, clean, low-cost, environmentally friendly, nontoxic, reliable, and safe approach that can be used for a range of applications.

AuNPs were synthesized from algae *Chlorella vulgaris. Chlorella* is a genus of single-cell green algae belonging to the division Chlorophyta of family Chlorellaceae. *Chlorella* is spherical in shape, approximately 2–10 µm in diameter, and is without flagella [49].

Sargassum wightii were used to synthesize AuNPs. *Sargassum* is a genus of brown algae that belongs to class Phaeophyceae in the order Fucales. Numerous species are distributed throughout the temperate and tropical oceans of the world, where they generally inhabit shallow water and coral reefs, and the genus is widely known for its planktonic (free-floating) species. In their study, they described the extracellular biosynthesis of AuNPs using *Sargassum wightii* and produced AuNPs within a short duration. The TEM showed the well-dispersed spherical AuNPs in the range, 8–12 nm. X-ray diffraction (XRD) of the AuNPs exhibited Bragg reflections corresponding to AuNPs [45].

Plectonema boryanum were used to synthesize AuNPs. It is blue–green algae and forms spuriously branched, usually blue–green, single-stranded filaments with a diameter of 0.7–22 µm. Their cylindrical cells, like all bacteria, contain neither nuclei nor plastids and belong to the family Oscillatoriaceae [50].

The eco-friendly approach to the synthesis of AuNPs nanoparticles were done using the aqueous extract of marine algae *Gracilaria corticata*, as a reducing agent. The biosynthesized AuNPs were confirmed by UV–visible spectroscopy and scanning electron microscopy (SEM).

Table 1 List of algae used to synthesize gold nanoparticles

S. No.	Algae	Size (nm)	Shape	References
1	*Sargassum wightii*	8–12	Spherical	[45]
2	*Laminaria japonica*	15–20	Spherical self-assembled	[47]
3	*Stoechospermum marginatum*	18.7–93.7	Hexagonal and triangle	[48]
4	*Gracilaria corticata*	45–57	Spherical	[51]
5	*Rhizoclonium hieroglyphicum*	< 20	Spherical	[52]
6	*Sargassum muticum*	< 10	Spherical and crystalline	[55]
7	*Pithophora oedogonia*	32.06	Spherical	[56]
8	*Chlorella pyrenoidusa*	25–30	Spherical	[59]
9	*Acanthophora spicifera*	27–35	Spherical	[58]
10	*Sargassum myriocystum*	15	Triangular and spherical	[60]
11	*Stoechospermum marginatum*	18.7–93.7	Hexagonal and triangle	[61]
12	*Laminaria japonica*	15	Spherical	[62]
13	*Turbinaria conoides*	6–10	Spherical	[80]
14	*Porphyra spp*	13 ± 5	Spherical	[81]
15	*Galaxaura elongate*	3.85–77.13	Hexagonal	[84]
16	*Padina pavonica*	30–100	Spherical	[85]
17	*Tetraselmis suecica*	79	Spherical	[87]
18	*Sargassum incisifolium*	12.38	Spherical	[89]
19	*Rhizoclonium fontinale*	7.92	Spherical	[90]
20	*Ulva intestinalis*	17	Triangular	[90]
21	*Chara zeylanica*	24	Triangular	[90]
22	*Pithophora oedogoniana*	15	Spherical	[90]
23	*Tetraselmis kochinensis*	5–35	Spherical	[91]
24	*Padina gymnospora*	53–67	Spherical	[92]
25	*Fucus vesiculosus*		Spherical	[93]
26	*Cystoseira baccata*	8.4 ± 2.2	Spherical & polycrystalline	[94]
27	*Osmundaria obtusiloba*	10–20	spherical, triangular and diamond	[95]
28	*Padina tetrastromatica*	8–10	Spherical	[98]
29	*Kappaphycus alvarezii*		Spherical	[99]
30	*Ulva fasciata*	10 ± 3	Spherical	[101]

Table 2 List of blue–green algae used to synthesize gold nanoparticles

S. No.	Algae	Size (nm)	Shape	References
1	*Plectonema boryanum*	< 10	Octahedral	[57]
2	*Spirulina platensis*	20–30	Spherical	[65, 82]
3	*Calothrix* spp.	< 100	Spherical	[83]
4	*Phormidium valderianum*	< 100	Hexagonal and triangular	[90]
5	*Microcoleus chthonoplastes*	< 100	Hexagonal triangular	[90]

The SEM images showed well-distributed AuNPs nanoparticles with sizes ranging from 45 to 57 nm. The synthesized AuNPs were screened against bacterial pathogen Gram-positive *Staphylococcus aureus, Enterococcus faecalis*, and Gram-negative *Escherichia coli*, and *Enterobacter aerogenes*, and also assessed for their antioxidant activity by a DPPH free radical scavenging assay and ferric-ion reducing ability and antioxidant power assay. The antibacterial and antioxidant activity of the AuNPs revealed an appreciable approach compared to the standard. These data provide a green approach to the synthesis of AuNPs particles as well as a new way for new pharmaceutical leads [51].

AuNPs have been synthesized using blue–green algae, such as *Spirulina subsalsa*, which is blue–green algae and belongs to the family Spirulinaceae. *Rhizoclonium hieroglyphicum* and *R. riparium* is a green algae that belongs to the family Cladophoraceae, and diatoms *Nitzschia obtusa* and *Navicula minima* have recently been reported by Chakraborty et al. [52, 53] and Nayak et al. [54]. *Nitzschia*

is a common pennate marine diatom that belongs to the family Bacillariaceae.

The green biosynthesis of AuNPs was done by interacting the extract of *Sargassum muticum*. The synthesized AuNPs were characterized by UV–Vis, zeta potential, and TEM. The AuNPs were spherical and crystalline, and exhibited a size of < 10 nm. They also reported the in vitro anticancer activity in human leukemia cell lines. The nature of the inhibition of cancer cell growth by AuNPs could open the way for further research in the design of green syntheses of therapeutic agents, particularly in nanomedicine for the treatment of cancer [55].

The biosynthesis of AuNPs was done using green algae *Pithophora oedogonia* as a reducing agent. During this approach, AuNPs formed rapidly within 1 h by the interaction of Au salt with the algal extract. Spectral techniques were used to confirm their formation. UV–Vis spectroscopy and X-ray photoelectron spectroscopy confirmed the formation of metallic Au. SEM and dynamic light scattering revealed the biosynthesized AuNPs to have a mean size of 32.06 nm. The biosynthesis of AuNPs has applied to screen printed electrode surface modification and showed excellent electrolytic activity towards the determination of carbendazim molecules in soil [56].

AuNPs were synthesized from *Plectonema boryanum* UTEX 485, a filamentous cyanobacterium or blue–green algae, by a reaction with aqueous $Au(S_2O_3)_2^{3-}$ and $AuCl_4^-$ solutions (~400–550 mg/L Au) at 25–100 °C for up to 1 month and at 200 °C for 1 day. The interaction of cyanobacteria with aqueous Au $(S_2O_3)_2^{3-}$ promoted the precipitation of cubic (100) AuNPs (< 10–25 nm) at the membrane vesicles and admixed with gold sulfide within the cells and encrusted on the cyanobacteria. In contrast, the reaction with $AuCl_4^-$ resulted in the precipitation of octahedral (111) gold platelets (~1–10 µm) in solution and nanoparticles of gold (< 10 nm) within the cells. The functional groups imaged by negative ion TOF–SIMS on the (111) faces of the octahedral platelets were predominantly Cl and CN^-, with smaller amounts of C_2H and CNO [57].

AuNPs synthesized from *Acanthophora spicifera*, which is a species of marine red algae in the family Rhodomelaceae. *A. spicifera* is one of the most common non-indigenous algal species in Hawaii and has displaced many native species where it is abundant [58].

The biosynthesis of stable AuNPs was done using a *Chlorella pyrenoidusa* extract. The most dominating parameters for the synthesis of AuNPs were pH 8, 100 °C, and 100 ppm aurochlorate salt. The synthesis of AuNPs was confirmed by UV–Vis spectroscopy, XRD, and high-resolution transmission electron microscopy. HRTEM and the SPR peaks of the UV–Vis spectra revealed AuNPs, 25–30 nm in size. HRTEM showed spherical nanoparticles at alkaline pH (pH 8), whereas an anisotropic nanostructure was obtained at pH 4 [59].

Sargassum myriocystum algae were used as a reducing agent to synthesize AuNPs. *Sargassum* is a genus of brown (class Phaeophyceae) macroalgae (seaweed) in the order Fucales. Numerous species are distributed throughout the temperate and tropical oceans of the world, where they generally inhabit shallow water and coral reefs. The genus is widely known for its planktonic (free-floating) species [60].

AuNPs synthesized from *Stoechospermum marginatum. Stoechospermum marginatum* is a brown alga of the class Phaeophyceae. The alga is a rigorously forking plant that may reach a length of 40 cm; the plants are usually 20–30 cm long and 8–11 mm broad; thallus flat, erect, dichotomously branched without a midrib; margin entire; apex bifid or flatly truncate; section of thallus, greater part with large parenchymatous cells in the middle and on either side covered by two layers of small cells; fertile plants are easily identified by the marginal dark lines of crowded sporangia [61].

Laminaria japonica algae used to synthesize AuNPs. *Laminaria* is a genus of 31 species of brown algae commonly called kelp. Some species are also referred to as tangle. This economically important genus is characterized by the long, leathery laminae and relatively large size. Some species are referred to by the common name Devil's apron because of their shape [62]. The bactericidal effects of AuNPs depend on the size and shape of the particle [63, 64].

AuNPs synthesized from *Spirulina platensis* (Fig. 5) and examined their antibacterial activity [65]. Gold metal is precious and less toxic, and has been exploited to treat various diseases. AuNPs exhibited various utility in nanobiotechnology as biomedicine because of the convenient surface bioconjugation with biomolecular investigation and surprising plasmon resonance optical properties [66–68]. The biosynthesized AuNPs have attracted interest for the migration of nucleic acids, proteins, gene therapy, drug delivery, and targeting [69].

Macroalgae have a broad range of biological activities, such as antibacterial [70], anticoagulant [71], and antifouling activity [72]. Over the last decade, algae found as seaweeds have been used in medicine as vermifuges, esthetics, and antibiotics in the treatment of coughs, wounds, gout, goiter, hypertension, venereal diseases, cancer, and a variety of other diseases [73]. *T. conoides* is a brown colored algae belonging to the order Fucales and in the family Sargassaceae. They contain sterols, such as fucosterol, and different molecules containing vinyl and ethyl cholesterol types, and cyclohexane [74]. Some chemical compounds obtained from the brown algae, such as sulphated polysaccharides including fucoidan, neutral glucan, guluronic, and mannuronic acid residue-containing alginic acid [75], rhamnose, fucose, arabinose, xylose, mannose, galactose, glucose, and uronic acids [76], have medicinal uses. Despite this,

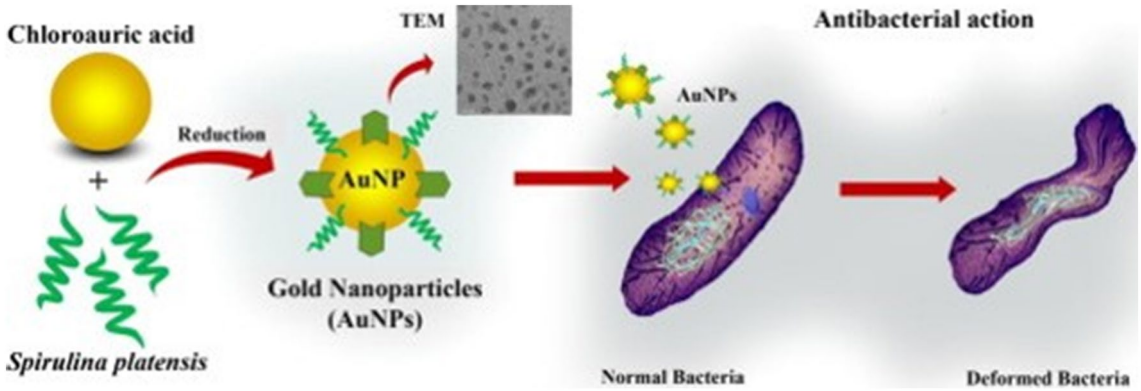

Fig. 5 AuNPs synthesis from *Spirulina platensis* and its antibacterial activity [65]

the polysaccharide and protein biomolecules in the algae extract can be used to reduce the gold ions and produce AuNPs. The algal-mediated AuNPs' synthesis mechanism exhibits electrostatic interactions between gold anions and algal functional groups. The interaction occurs between the $AuCl_4^-$ anion and amino groups, which is bound to the surface of algae. During the reaction, the algal extracts reduced Au(III) to AuNPs. This was attributed to the presence of hydroxyl groups in the brown algal polysaccharides used in the bioreduction of Au(III) ions to Au(0) [77].

Noruzi et al. [78] and Raghunandan et al. [79] reported the biosynthesis of algal-mediated AuNPs. The synthesized AuNPs were conglomerates of spherical, triangular, and pseudo-spherical shapes.

The green synthesis of AuNPs was reported using the algae extract of *Turbinaria conoides. T. conoides* is a genus of brown algae. The formation of AuNPs was confirmed initially by the color change from yellow to dark pink in the reaction mixture, and spectral evidence, such as the broad surface plasmon resonance band, was centered at 520–525 nm, which provides information on polydispersed nanoparticle formation. Finally, the structure was confirmed by TEM and the crystalline structure of synthesized Au with a size range of 6–10 nm. In the other case, the biosynthesis of AuNPs was achieved using marine algae *Cladosiphon okamuranus (o-fucoidan*), *Cladosiphon okamuranus* (*mozuku*), which is a type of edible seaweed in the genus *Cladosiphon*, naturally found in Okinawa, Japan. Most mozuku is now farmed by locals, and sold to processing factories. Mozuku is used mainly as food, and as a source of one type of sulphated polysaccharide called fucoidan, which is used as a cancer treatment aid and health supplement. Fucoidans contain sulphated polysaccharides found in marine algae *Cladosiphon okamuranus* and *Kjellamaniella crassifolia* [Rajeshkumar et al. 80].

The one-pot size-controlled green synthesis of AuNPs was done using *Porphyran* (red seaweed) as a reducing agent. Porphyran is a sulphated carbohydrate derived from the red algae of the genus *Porphyra*. The synthesized AuNPs are used as a carrier for the delivery of an anticancer drug. Porphyran was used as a reducing agent for the controlled green synthesis of AuNPs and has biological potential as a carrier for the delivery of anticancer drugs. The synthesized AuNPs were monitored using a spectral technique. The formation of AuNPs was confirmed by surface plasmon resonance centered at 520 nm with a mean size range of 13 ± 5 nm. The FTIR spectra suggest that the sulfate moiety is responsible mainly for the reduction of chloroauric acid. The capping of the AuNPs with porphyran was confirmed by the negative zeta potential values responsible for the electrostatic stability. Therefore, porphyran acts as both a reducing and capping agent. The synthesized AuNPs were highly stable in a wide range of pH and electrolyte concentrations. Porphyran-capped AuNPs enhanced the cytotoxicity on the human glioma cell line (LN-229) compared to native porphyran (Fig. 6). The AuNPs were also used as a carrier for the delivery of the anticancer drug, doxorubicin hydrochloride (DOX). Spectroscopic support showed that DOX was conjugated to the AuNPs via hydrogen bonding. The release of DOX from the DOX-loaded AuNPs was six times higher in acetate buffer (pH 4.5) than in physiological buffer (pH 7.4). In this light, the DOX-loaded AuNPs demonstrated higher cytotoxicity to the LN-229 cell line compared to that of an equal dose of a native DOX solution. The biosynthesized AuNPs have potential use as a carrier for anticancer drug delivery [81].

The synthesis of AuNPs was done using a very well-slaked microorganism known as blue–green algae *Spirulina platensis*. The finally isolate products or complex of optical and analytical methods was applied as an experimental sample after exposure to a chloroaurate ($HAuCl_4$) solution at different doses and for different times. The synthesized compounds were characterized by UV–visible spectroscopy, TEM, SEM, and energy-dispersive analysis of X-ray

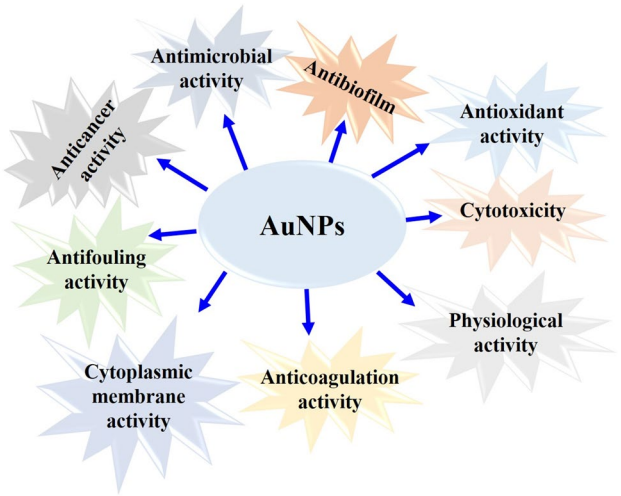

Fig. 6 Biological activities of the AuNPs

(EDAX). After 1.5–2 days, extracellular spherical nanoparticles, 20–30 nm in size, formed. Neutron activation analysis (NAA) was used to determine the gold concentration in the *Spirulina platensis* biomass [82].

The ultrasound-assisted synthesis of AuNPs, in an eco-friendly approach in the presence of *Calothrix* blue–green algae was reported. *Calothrix* belongs to the order nostocales and family Rivulariaceae. The synthesized AuNPs in the reaction mixture is stimulated materially by producing ultrasound irradiation. The optical properties, size distribution, morphology, and crystalline phase of the AuNPs were confirmed by spectral evidence, such as UV–visible spectroscopy, dynamic light scattering, TEM, and XRD techniques. During synthesis, a light pink color appears at the range, $\lambda_{max} = 550$ nm, indicating the formation of AuNPs. The TEM image provides information on anisotropic AuNPs with a predominant truncated shape, 30–120 nm in size. The XRD pattern of the AuNPs exhibited a Bragg reflection peak at 38.23° 2θ, corresponding to elemental gold [83].

The synthesis of AuNPs was reported using *Galaxaura elongate* (powder or extract), which is a genus of thalloid red algae. The rapid formation of stable AuNPs was achieved using *G. elongata* extract in an aqueous medium under normal atmospheric conditions. TEM confirmed that the particles were spherical in shape with a few rods, and triangular, truncated triangular, and hexagonal-shaped AuNPs. The zeta potential showed that the AuNPs were 3.85–77.13 nmin size. FTIR spectroscopy showed that the AuNPs were capped with the algae compound. The chemical constituents of the algae extract, i.e., andrographolide, alloaromadendrene oxide, glutamic acid, hexadecanoic acid, oleic acid, 11-eicosenoic acid, stearic acid, gallic acid, epigallocatechin catechin, and epicatechin gallate, may act as a reducing, stabilizing, and capping agent. The AuNPs were screened for their antibacterial activities, which showed better antibacterial effects with maximum inhibition zones of 17–16 nm by the AuNPs synthesized by the ethanolic extract against *Escherichia coli, Klebsiella pneumonia*, and MRSA followed by *Staphylococcus aureus*, and *Pseudomonas aeruginosa* (13 nm). The AuNPs synthesized by the *G. elongate* powder were quite effective against *E. coli* and *K. pneumoniae* (13.5 and 13 nm). On the other hand, the free ethanolic extract of *G. Elongate* exhibited high activity against MRSA (14 mm), respectively [84].

A novel way was used to synthesize AuNPs via an eco-friendly biological approach using *Padina pavonica* alga within 24 h. *Padina pavonica*, which is commonly known as Peacocks tail, is a brown alga found in the Atlantic Ocean and Mediterranean Sea. The particle size was analyzed by XRD and size range of the AuNPs was calculated to be 30–100 nm. The TEM and EDX data exhibited a spherical morphology of AuNPs and elemental composition. FTIR spectroscopy confirmed the reduction of Au. The antimicrobial activity of the AuNPs was tested against *Escherichia coli* and *Bacillus subtilis*. The inhibition zone diameter in *B. subtilis* was 15 mm and much less in the case of *E. coli* [85].

The green synthesis of AuNPs was reported using the aqueous extract of the seaweed *Turbinaria conoides* and examined its antibiofilm activity against marine biofilm-forming bacteria. UV–Vis spectroscopy revealed the characteristic SPR absorption band at 538 nm for AuNPs. The biosynthesized nanoparticles were examined further using FTIR, XRD, FESEM, EDX, and HRTEM. The data revealed the spherical and triangular nanostructure of AuNPs with a size range of 2–19 nm [86].

AuNPs were synthesized within a short time using a fresh cell extract of the marine microalga *Tetraselmis suecica* as a reducing agent for the $HAuCl_4$ solution. The synthesized AuNPs were confirmed by UV–visible spectroscopy of the aqueous medium containing AuNPs, which revealed a peak at 530 nm. The XRD pattern also showed a Bragg reflection related to AuNPs. FTIR spectroscopy was performed for the analysis of surface functional groups of AuNPs. TEM and the particle–size distribution pattern by laser light scattering method confirmed the formation of well-dispersed AuNPs. The most frequent particle size was 79 nm [87].

The biosynthesis of self-assembled AuNPs was reported using an aqueous extract of green microalga, *Chlorella vulgaris*. The optical, physical, chemical, and bactericidal properties of the AuNPs as well as their shape and size, crystal structure, and surface chemistry were examined by UV–visible spectroscopy, SEM, TEM, XRD, FTIR spectroscopy, and antimicrobial activity. The synthesized AuNPs exhibited spherical self-assembled cores of the synthesized AuNPs ranging from 2 to 10 nm. Biological screening against the human pathogen *Candida albicans* and *Staphylococcus aureus* revealed them to be susceptible to synthesized

aqueous AuNPs. Therefore, biosynthesis, stabilization, and self-assembly of the AuNPs by *Chlorella vulgaris* extract can be used in green chemistry and an effective drug (Fig. 6) [88].

The synthesis of AuNPs using two different aqueous extracts of the brown algae *Sargassum incisifolium* was done. The cost effectiveness of the extract in developing AuNPs was compared with commercially found brown algal fucoidans with the major constituent of brown algal aqueous extract. The rate of AuNP synthesis was monitored by UV–Vis, and the related size, shape, and morphology of the AuNPs were confirmed by TEM. The analyses revealed spherical AuNPs with a mean size of 12.38 nm. The AuNPs were screened for a biological assay against two Gram-negative bacteria, two Gram-positive bacteria, and one yeast strain. The AuNPs displayed negligible toxicity [89].

The effects of the cyanobacteria *Phormidium valderianum, P. tenue*, and *Microcoleus chthonoplastes*, and the green algae *Rhizoclonium fontinale, Ulva intestinalis, Chara zeylanica*, and *Pithophora oedogoniana* on a hydrogen tetrachloroaurate solution for producing AuNPs. The hydrogen tetrachloroaurate interacted with all three cyanobacteria genera and two of the green algae (*Rhizoclonium fontinale* and *Ulva intestinalis*) to fabricate AuNPs intracellularly, which produced a purple coloration of the thallus within 72 h of treatment at 20 °C. The extracted AuNPs' solution was examined by UV–Vis spectroscopy, TEM and XRD. XRD confirmed the reduction of Au(III) to Au(0). UV–Vis spectroscopy and TEM confirmed the formation of AuNPs with different shapes and sizes. The *Phormidium valderianum*-synthesized AuNPs were mainly spherical AuNPs, but hexagonal and triangular nanoparticles were formed at basic and neutral pH (pH 9 and pH 7), respectively. At pH5, the AuNPs of *P. valderianum* exhibited a spherical size, 15 nm in diameter, along with a few nanorods, approximately 11–32 nm in length. At pH7, mostly spherical particles, 7.92 nm in size, were also observed with a few large particles, 17 nm in size. On the other hand, a few AuNPs with a triangular shape, 24 nm in size, were observed at this pH. At pH 9, most of the AuNPs particles were spherical, 13.78 nm in size, along with a few hexagonal particles, 25 nm in size. The medicinally important Au nanorods were synthesized (together with gold nanospheres) only by *P. valderianum* at acidic pH (pH5). This was determined initially by two surface plasmon bands in UV–Vis spectroscopy and finally confirmed by TEM. Spherical and irregular particles were produced by *P. tenue* and *Ulva intestinalis*, respectively. The AuNPs were spherical irregular in shape, 14.84 nm in size; similar results were obtained from *U. intestinalis* treated at pH 5, but the AuNPs were larger (42.39 nm). The formation of AuNPs by algae is more eco-friendly than pure chemical synthesis. Despite this, the choice of algae is an essential factor, because *Chara zeylanica* and *Pithophora oedogoniana* were unable to produce nanoparticles. The other two eukaryotic algae, *Chara zeylanica* and *Pithophora oedogoniana*, exhibited gold toxicity and the thallus turned pale green instead of becoming pink, indicating cell death [90].

The eco-friendly biosynthesis of AuNPs was done using alga *Tetraselmis kochinensis* in the intracellular region with a size range of 5–35 nm. *Tetraselmis* is a green algal genus of phytoplankton within the order Chlorodendrales that are characterized by their intense green colored chloroplast, flagellated cell bodies, presence of a pyrenoid within the chloroplast, and a scale-producing the cell wall. These AuNPs have a strong effect on the cell wall compared to the cytoplasmic membrane due to the reduction of metal ions by enzymes present in the cell wall and cytoplasmic membrane. These AuNPs can be applied in the field of drug delivery, biomedical application, and catalysis [91].

A reliable and eco-friendly approach for the biosynthesis of AuNPs was developed using *Padina gymnospora*, which was achieved in a short duration. *Padina gymnospora* belongs to class Phaeophyceae. SEM showed the formation of well-dispersed AuNPs. The FTIR spectra of brown algae confirmed that the hydroxyl groups present in the algal polysaccharides were involved in gold bioreduction. AFM revealed a particle-size range (53–67 nm) and mean particle roughness (60.0 nm). XRD of the AuNPs exhibited Bragg reflections corresponding to AuNPs. In addition to methods' application, this environmentally friendly approach of biological AuNPs synthesis has potential use in various products, such as cosmetics, foods, and consumers goods [92].

The bioreduction of Au(III) to Au(0) was reported using the biomass of the brown alga *Fucus vesiculosus. F. vesiculosus*, which is known by the common name bladder wrack, is a seaweed found on the coasts of the North Sea, western Baltic Sea, and Atlantic and Pacific Oceans, and is also known by the common names black tang. *Fucus vesiculosus* belongs to the class Phaeophyceae. During the process, the reaction was completed in two steps, such as recovery and reduction at different pH 4–9 and pH 7. In the first stage, the reduction of gold at various pH was practically negligible and no color change was observed. In the second stage, Au reduction occurs with a sharp decrease in concentration, pH, and redox potential, and showed a color change from yellow to reddish purple. The hydroxyl group present in the algal polysaccharides was involved in Au^{3+} bioreduction. Metallic gold was detected as microprecipitates on the biomass surface and in colloidal form as nanoparticles in solution. The synthesis of AuNPs using the biological approach from *F. vesiculosus* is an alternative and environmentally friendly methodology that has been used to collect gold from dilute hydrometallurgical solutions and leachates of electronic scraps as well as for the synthesis of AuNPs with different sizes and shapes [93].

The synthesis of AuNPs using a brown macroalgae *Cystoseira baccata* extract and developed an eco-friendly, fast, and one-pot synthetic approach. *C. baccata* is a species of brown seaweed in the family Fucaceae that is found in the north east Atlantic, Baltic Sea, and Mediterranean Sea. The species name *baccata* means berry-like and refers to the small air bladders. In this regards, the biosynthesized AuNPs were examined by UV–Vis spectroscopy, TEM, HRTEM, SEM, and zeta potential measurement; the results revealed spherical, stable, and polycrystalline with a mean diameter of 8.4 ± 2.2 nm. The extract was used as a protective agent where the particles were embedded, keeping them separated, thereby avoiding aggregation and coalescence. EDS analysis confirmed the elemental composition of the extract and nanoparticles. Therefore, the functional group of the biomolecules on *C. baccata* and Au@CB (*C. baccata*) was characterized by FTIR. The effects of the CB extract and Au@CB were tested in vitro on the colon cancer cell lines HT-29 and Caco-2, and on a normal primary neonatal dermal fibroblast cell line, PCS-201-010. The result revealed a stronger cytotoxic effect against HT-29 than Caco-2; interestingly, a lack of toxicity on PCS-201-010 was observed. Finally, an examination of the apoptotic activity showed that Au@CB could activate apoptosis by the extrinsic and mitochondrial pathway in the CRC in vitro model. These encouraging results suggest that Au@CB has a significant potential for the treatment of rectal cancer [94].

In this work, an eco-friendly approaches for the synthesis of AuNPs by taking the macroalgae *Osmundaria obtusiloba*. *Osmundaria* belongs to class Rhodophyceae. The optical properties of the synthesized AuNPs were evaluated and compared with the AuNPs obtained by the traditional approach. The UV–Vis spectra showed a peak at 540 nm, confirming the formation of AuNPs. The XRD pattern confirmed a face-centered cubic (FCC) crystalline structure for these AuNPs. The HRTEM image revealed several shapes, including spherical-, triangular-, and diamond-shaped AuNPs with a size range between 10 and 20 nm. The presence of 83.58 wt% elemental Au in the obtained AuNPs was confirmed by EDS. In addition, their utility as a fluorescence quencher or enhancer was evaluated using methyl orange [95].

Biogenic and eco-friendly AuNPs were synthesizing using algae as a bio-reagent. The efficacy of a chlorophycean microalga, *Spirogyra submaxima* for AuNPs synthesis using an aurotetrachlorate solution, was revealed. *Spirogyra* (common names include water silk, mermaid's tresses, and blanket weed) is a genus of filamentous chlorophyte green algae of the order Zygnematales, named for the helical or spiral arrangement of the chloroplasts that is indicative of the genus. The genus is commonly found in fresh water areas, and there are more than 400 species of *Spirogyra* in the world. The algal biomass turned purple after 24 h exposure to an aqueous Au(III) solution due to the formation of AuNPs by the bioconversion of Au(III) to Au(0) at the intracellular level. The AuNPs were extracted from algal biomass using a sodium citrate solution as a capping agent and subjected to different experiments for their characterization. The specific plasmon band, size, and morphology were identified by UV–Vis spectroscopy and TEM. Dynamic light scattering (DLS) revealed the average hydrodynamic diameter of the particles distributed in a citrate solution. Four major peaks at 38.20, 44.50, 65.60, and 78.60°2θ obtained from XRD confirmed the presence of elemental gold. The charges around the particles (-11.9 mV) were observed by the zeta potential study. Overall, this technique requires low energy and has low manufacturing cost [96].

The rapid synthesis of AuNPs was done using novel marine brown alga *Ecklonia cava* of the family Lessoniaceae by the reduction of chloroauric acid. *E. cava* is an edible marine brown alga species found in the ocean around Japan and Korea. The reaction was completed within 1 min at 80 °C; the formation of AuNPs was observed by a color change. The biosynthesis of AuNPs was confirmed by spectral evidence. FTIR spectroscopy showed that AuNPs were functionalized with biomolecules with a primary amine group, hydroxyl group, and other stabilizing functional groups. XRD revealed high purity and the face-centered cubic structure of AuNPs. The AuNPs were spherical and triangular with a mean size of 30 ± 0.25 nm. The synthesized AuNPs showed good antimicrobial properties and biocompatibility with the human keratinocyte cell line (Fig. 6). An examination of the physiological characteristics showed that the AuNPs have encouraging biomedical applications in different areas, such as drug delivery, tissue engineering, and biosensors [97].

The biosynthesis of AuNPs was done using marine brown seaweed *Padina tetrastromatica* as a both reducing and capping agent. *Padina* is a type of brown algae of the family Dictyotaceae. The AuNPs were optimized by changing the concentration of algae extract, pH, and temperature. The synthesized AuNPs were examined by UV–Vis spectroscopy, XRD, FTIR spectroscopy, SEM, TEM, EDX, and SAED. FTIR spectroscopy showed that the extract-containing OH as a functional group (sugar molecules) acts by capping the AuNPs synthesis. The SEM image showed that all particles were spherical in shape. TEM confirmed the spherical shape with a mean size of 8–10 nm. The synthesized AuNPs were assessed for their in vitro cytotoxic activity on human liver cancer (Hep G2) and lung cancer (A549) cell lines at different concentrations by a comparison with that of the standard drug, cyclophosphamide [98].

Biosynthesis of AuNPs was done using marine alga *Kappaphycus alvarezii* and scrutinizes its efficiency to reduce gold ions to AuNPs. *Kappaphycus alvarezii*, which is known as elkhorn sea moss, is a species of red algae. This is one of

the most important commercial sources of carrageenan, a family of gel-forming, viscosifying polysaccharides. Farming methods affect the character of carrageenan that can be extracted from seaweed. They reported AuNPs' synthesis using the aqueous extract of *K. alvarezii* with aqueous gold ions within the biomass extracellularly. The synthesized AuNPs were examined by UV–Vis spectroscopy, FTIR spectroscopy, SEM, TEM, and XRD. In addition, they also developed the rapid extracellular formation of spherical AuNPs by a reaction of gold ions and *K. alvarezii* biomass under stationary conditions. The AuNPs were nontoxic to the cells that continued to grow after the biosynthesis of AuNPs [99].

An extract of brown seaweed, *Turbinaria ornate* was examined for the biosynthesis of AuNPs. The synthesized AuNPs were examined by UV–Visible spectroscopy, FTIR spectroscopy, XRD, SEM, and EDX. The prepared AuNPs exhibited distinct surface plasmon peaks at 525 nm and the color of the reaction mixture changed gradually from brown to ruby red. Elemental gold was also confirmed by EDX. SEM and TEM provide information on the confirmed size and shape of the synthesized AuNPs, which exhibited a spherical shape with a mean particle size of 7–11 nm [100].

A facile, green, and high yielding method for the synthesis and stabilization of monodisperse AuNPs was developed using a green seaweed *Ulva fasciata* extract. TEM revealed a spherical shape with a size range of 10 ± 3 nm. FTIR spectroscopy also revealed the role of phytochemical of the *Ulva fasciata* extract for the bioreduction and stabilization of AuNPs. The synthesized AuNPs showed remarkable catalytic efficiency by the reduction of 4-nitroaniline by potassium borohydride in an aqueous solution using UV–visible absorption spectroscopy. Catalytic reduction followed pseudo-first-order kinetics with respect to 4-nitrophenol [101].

The aqueous extract of *Sargassum myriocystum* was used for the biosynthesis of AuNPs by the reduction of chloroauric acid. During the reaction, the AuNPs were formed within 15 min at 76 °C, which were determined by spectroscopic techniques. The size, shape, and elemental composition of AuNPs were examined by UV–Vis spectroscopy, FTIR spectroscopy, TEM, SEM–EDX, and XRD. The newly developed AuNPs were stable, well-defined, polydispersed (triangular and spherical) and crystalline with a mean size of 15 nm. The biomolecules involved in stabilizing AuNPs were identified by gas chromatography–mass spectrometry GC–MS [102].

The biosynthesis of AuNPs was done using marine macroalgae, *Padina gymnospora*, and attributed their bio system applications to their optical properties in the form of plasmon resonance and amperometric properties with very low or no immediate toxicity. In this case, high-resolution imaging techniques were performed on different length scales to determine the morphology of AuNPs. The effects of the macroalgae decoction concentration on the formation of AuNPs (8–21 nm) were studied further to determine the functional and molecular mechanism of cell death on a liver cancer (HepG2) cell line and lung cancer (A549) cell line. The AuNP-induced cell death in the human carcinoma liver cell line HepG2 but not in the lung cancer cell line. The induction specificity for the death response in lung cells showed that AuNPs do not universally target all cell types. Altered DNA fragmentation and cell staining in different cancer cells suggest the potential for in vivo applications of AuNPs. Therefore, more study will be needed to evaluate the interactions of nanomaterials with biomolecules and cellular components for controlled cancer therapy [103].

Tables 1 and 2 summarize the list of algae and blue–green algae used for the extracellular or intracellular syntheses of gold nanoparticles, respectively.

Future prospects

The synthesis of AuNPs using algae has attracted considerable interest over the last few decades, because the process is simple, clean, safe, environmentally friendly, and does not produce toxic chemicals. The interest in the use of algae for nanoparticle synthesis has increased because of the rapid and environmentally 'clean' nanobiofactories of metallic nanoparticles. The essence of algal nanobiotechnology as an appropriate biogenic approach for the synthesis of different types of nanomaterials is well recognized with great potential and promise for advanced diagnostics, biosensors, and smart target delivery systems. In the future, the following issues will need to be addressed, ranging from algal and nanobiotechnology points of view for the sustainable and precise syntheses of AuNPs and its applications:

- The mechanisms of nanoparticle synthesis will need to be examined using different types of algae that have not been studied clearly. Comprehensive studies will be needed to understand the precise mechanisms of the reaction to recognize the proteins and enzymes involved in algal nanoparticle synthesis. The development of simple and low-cost techniques to make the synthesis procedure commercially available should be considered.
- The size, shape, and monodispersity are the three important parameters for the synthesis of nanoparticles using algae. Therefore, effective control of the particle size, shape, and mono dispersity is needed by varying the synthesis parameters, such as the algae type, cultivation medium, growth stage, synthesis conditions, substrate concentrations, reaction time, pH, and temperature.
- The interaction of algae with precursors results in nanoparticles with various sizes and morphologies. The bio-

logical potentials of algae and blue–green algae for the synthesis of gold nanoparticles provide a convenient synthesis route with a better control over the morphology of nanoparticles. Therefore, experimental trials will be needed to better understand the detail synthesis and morphological control.

- Algae can be used to develop natural nanofactories for gold nanoparticles synthesis. Currently, algae-assisted synthesis of nanomaterials with varying compositions are limited and confined to metal nanoparticles. Therefore, an expansion of this protocol will enable the green synthesis of nanomaterials, such as metal oxides, nitrides, carbides, sulfides, etc., required to make algae-assisted synthesis commercially available.
- Nanobiotechnology has the potential to revolutionize human health, and agricultural and food industries with novel tools for the treatment of diseases as well as for rapid disease detection. Therefore, effective means of examining the biological potential of algae and blue–green algae for the synthesis of AuNPs should be identified, and their behavior and accumulation within animals and plants should be studied.
- Future research will need to consider the size distribution and chemical composition of AuNPs synthesized using algae

Overall, nanobiotechnology that uses algae and blue–green algae to synthesize nanomaterials is still in its early stages and requires more in-depth research and development.

Summary

Gold nanoparticles (AuNPs) are one of the most widely used nanomaterials in commercial products because of their high electrical conductivity, optical properties, catalytic and effective antibacterial activities, and biocompatibility. In addition, AuNPs have been the most intensively studied nanomaterials in terms of their toxicity to bacteria, fungi, humans, and the environment. In recent years, nanomaterials, particularly AuNPs, were reported to behave unexpectedly due to the novel and exceptional characteristics when their particle size is downscaled to 1–100 nm. Therefore, the effects of microbes, plants, and animals have been studied. AuNPs are synthesized using chemical, photochemical, and biological methods. This review outlined the biosynthesis of AuNPs using various algae as well as blue–green algae and evaluated their biological potential. Algae have advantages over other microorganisms, such as high tolerance to harsh environmental conditions. The algae-assisted synthesis of AuNPs is cost-effective and environmentally friendly, because no toxic chemicals are involved. The biological potential/applications, such as antimicrobial, antibacterial, physiological, antibiofilm, antifouling, anticancer, anticoagulam, cytotoxicity, and antioxidant immune modulatory of the biosynthesized AuNPs were discussed, which have been attributed to their high surface-to-volume ratio. The applications of environmentally friendly AuNPs in vast fields have made them potentially popular and applicable. The biogenic synthesis of AuNPs using algae is a clean, low-cost, environmentally friendly, nontoxic, reliable, and safe approach that can be used for a range of applications.

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