CHAPTER

Benign fabrication of metallic/metal oxide nanoparticles from algae

19

Paulkumar Kanniah[a], Parvathiraja Chelliah[b], Jesi Reeta Thangapandi[a], Emmanuel Joshua Jebasingh Sathiya Balasingh Thangapandi[a], Murugan Kasi[a], and Sudhakar Sivasubramaniam[a]

[a]*Department of Biotechnology, Manonmaniam Sundaranar University, Tirunelveli, Tamil Nadu, India,*
[b]*Department of Physics, Manonmaniam Sundaranar University, Tirunelveli, Tamil Nadu, India*

1 Introduction

The association of materials with biology has built-up new criteria in the burgeoning newfangled part of nanotechnology and focused on developing biologically engineered nanostructured materials to amalgamate their profound research in nanobiotechnology. The study, synthesis, and commercialization of nanostructured materials are rapidly increasing day-by-day due to its promising and admirable applications in various fields, including clinical diagnosis, agriculture, medicine, electronics, solar cells, pharmaceuticals, and renewable energy (Jain, 2007; Rai and Ingle, 2012; Rai et al., 2016; Narayanan and Sakthivel, 2010; Sharma et al., 2019; Hussein, 2015). Nanomaterials are the sole source of nanotechnology, and based on the application point of view; the nanomaterials are tailored by surface modification with other metals/compounds/biomolecules (Narayanan and Sakthivel, 2010; Rai et al., 2016). In addition, tuning the nanomaterial size and shape impressively changes its physicochemical properties for enhanced activity (Wang et al., 2008; Cao et al., 2017; Pereira et al., 2015). However, the production of nanomaterials, both metallic and metal oxides, without causing any noxious effects, is a huge prominent concern in the arena of nanotechnology. Generally, classical methods such as chemical and physical methods are mostly used to produce nanostructured materials. Though, scientists found the classical methods are inappropriate and not fulfill the associated environmental issues. The unavoidable issues are as follows, (i) formation of toxic surplus compounds along with synthesized nanomaterials, (ii) requires high temperature, pressure, and plant, (iii) not an environmentally benign and expensive process (Narayanan and Sakthivel, 2010; Singh et al., 2016; Abbasi et al., 2016). These difficult problems turned on the scientists to focus on an alternative process that overcame the classical methods' issues. They have changed their focus on the biological sources used to remediate toxic pollutants in the environment (Narayanan and Sakthivel, 2010; Ojuederie and Babalola, 2017). They have found that some

Agri-Waste and Microbes for Production of Sustainable Nanomaterials. https://doi.org/10.1016/B978-0-12-823575-1.00007-X

microorganisms and plants have the potency to survive in the toxic chemical environment (Cabral et al., 2013; Yoon et al., 2006). The evolutionary changes in heavy metal tolerance behavior might be the possible reason that the microorganisms and plants obtained the ability to tolerate the chemical stress and utilize the chemicals as a nutrient for their growth and development at their minimum level. The proteins/enzymes/phytochemicals present in the microorganisms and plants play a significant role in the breakdown of toxic chemicals (Steinberg, 1936; Baldrian, 2003; Salam et al., 2016; Deng et al., 2004). The metal-microorganisms interaction phenomenon helped the researchers utilize the metal stress tolerant microorganisms to remediate toxic chemicals from the aquatic and terrestrial ecosystem. The *Pseudomonas stutzeri* AG259, AG257, AG643, and AG724 are the silver tolerant bacterial strains isolated from the silver mining area's soil by Klaus et al. (1999). Interestingly, they have found some of the nano-sized crystals around 200 nm on the poles of *Pseudomonas stutzeri* AG259 cells during the examination of silver tolerant behavior of *Pseudomonas stutzeri* AG259. Additionally, they reported the silver nanoparticles (Ag NPs) located in the periplasmic region due to the occurrence of silver specific binding proteins (Klaus et al., 1999). Like microorganisms, the plants also have the metal resistant ability that can undergo phytoremediation for their growth (Haverkamp and Marshall, 2009). In plants, roots are the important contact region for the transportation of metals or metal salts into the plant system. There is a vast confusion that metal nanoparticles formed outside of the plant (i.e.) in soil or after uptake of metals or metal salts can be converted to metal nanoparticle inside the plant system (Haverkamp and Marshall, 2009). To evident, a report by Gardea-Torresdey et al. (2003) exemplified the formation of silver nanoparticles inside the living alfalfa plants. Additionally, they stated the silver (Ag) and gold (Au) metals in the form of atoms (Ag^0 and Au^0) absorbed by the live alfalfa root and inside the plant system, they arranged each other to produce silver and gold nanoparticles (Gardea-Torresdey et al., 2003, 2002). These reports indicated that the availability of reducing candidates might influence the nucleation and growth of metal nanoparticles. Later, the extracts of various plant parts like leaf, fruit, seed, flower, stem, root, and bark were actively used to produce divergent nanoparticles. This chapter includes the participation of algae such as microalgae and macroalgae in the fabrication of various metal and metal oxide NPs an. We have explained in detail about the plausible mechanism involved in the production of nanoparticles. Besides, the possible biomolecules/phytochemicals participation and their functional activities in the nanoparticles synthesis process were also well documented.

2 Preference for plants

Mostly, the researchers preferred plant materials-based extracts to produce nanoparticles because of various active phytochemicals. The phytochemical constituents act as excellent reducing/capping/stabilizing agents in the formation of nanoparticles. Microorganisms are also eminent sources for the production of nanoparticles.

However, compared to plant materials, the microorganisms are failed to fulfill certain drawbacks. For instance, avoidance of cross-contamination is the primary demerit in the microbe mediated process. Maintaining a single microbial culture for the nanoparticles' production is a much tedious process in the laboratory condition. During synthesis, the environment should be maintained with an aseptic condition for escaping from the contamination (Kumar and Yadav, 2009; Vanaja et al., 2014; Shah et al., 2015). The plant-mediated synthesis process is simple, cheapest, non-toxic, eco-friendly, and has no microbial contamination (Kumar and Yadav, 2009; Shah et al., 2015). Therefore, nowadays, researchers are preferably chosen the plant materials for the production of metal and metal oxide nanoparticles.

Another important phenomenon is the involvement of prominent non-flowering algae in the production of nanoparticles. Like plant materials, the algae also have active phytochemicals that may participate in the synthesis of various nanomaterials. In the green synthesis process, the non-toxic reducing, capping/stabilizing agents, and admissible solvents are the important aspects. The algae-based NPs synthesis process also meet out all the mentioned criteria and amenable for the environment.

3 Algae

Algae are photosynthetic eukaryotes available in both fresh and marine water. The microalgae are the freshwater algae, and mostly they are a unicellular system. In contrast, marine water algae are macroalgae or seaweeds that hold a multicellular system (Chapman, 2013). Phycoremediation is the process that demonstrates the elimination of toxic pollutants from the contaminated sites by using algae. Among classical methods, the algae's utilization in removing toxic pollutants attained considerable attention due to its lesser influence on the environment (Baghour, 2019). In addition, it is a fine substitute for the microorganisms-based remediation approaches. The presence of a massive amount of enzymes in the algae has effective involvement in the degradation of noxious pollutants (Baghour, 2019; Tolboom et al., 2019). The microalgae such as *Chlamydomonas reinhardtii* (Zhang et al., 2011), *Chlorella* species (Wang et al., 2010), *Dunaliella* species (Imani et al., 2011), and *Chlorococcum* species (Subashchandrabose et al., 2015) actively participate in the bioaccumulation and degradation of toxic pollutants. The sewage is one of the right sources for the growth of microalgae because it can easily uptake the trace elements for their growth and development (Baghour, 2019). Hence, the microalgae are utilized mainly in the various industrial sewage treatment and municipal wastewater treatment plants. The microalgal biomass has remarkably used as biofertilizer in agriculture, in feed animal husbandry, and excellent source materials for biodiesel production (Mulbry et al., 2007; Madeira et al., 2017; Patil et al., 2011). Based on the biodegradation concept of algae, the nanoparticles of metal and metal oxide has been fabricated by the green route using algae in the field of nanobiotechnology. Furthermore, the NPs synthesized from algal materials have talented applications including antibacterial, antidiabetic, anticancer, antitumor, insecticidal, larvicidal, sensor, photocatalytic,

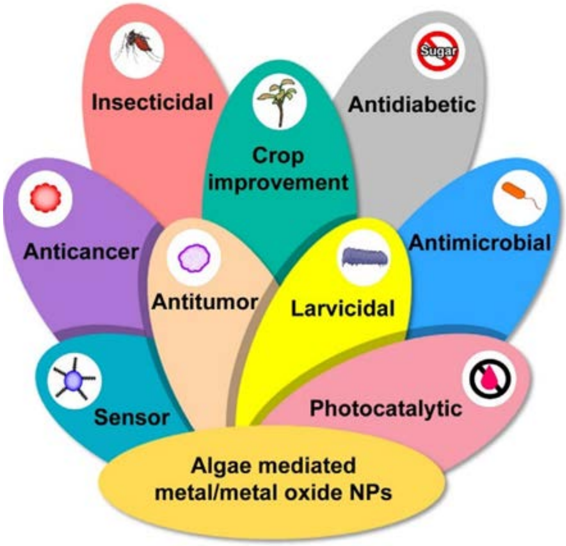

FIG. 1

Various applications of algae synthesized metal and metal oxide NPs.

and crop improvement (Govindaraju et al., 2009; Manam and Murugesan, 2014; Priyadharshini et al., 2014; Khalifa et al., 2016; Moorthi et al., 2015; Deepak et al., 2017; Momeni and Nabipour, 2015; Aziz et al., 2015; Venkatachalam et al., 2017) (Fig. 1).

4 Nanoparticles from microalgae

4.1 Metal NPs

The microalgae cells are tiny, and size ranges from few micrometers to tens of micrometers (Mata et al., 2012), which served as a green micro-machine in nanosized particle production. Generally, most researchers preferentially synthesized Ag and Au NPs using algal extract due to their promising biological activities. Green microalga *Scenedesmus* sp. is effectively used to synthesis 3–35 nm range sized Ag NPs through the intracellular process. In contrast, around 5–10 nm-sized silver nanoparticles were fabricated through the extracellular process. After exposure of silver nitrate to the algal cells, the silver ions were uptaken by the algal cells, and accumulation of silver ions was achieved 93% at the 72 h incubation. Inside the cells, the presence of protein moieties in the algal cells may be responsible for the biofabrication of Ag NPs (Fig. 2). While in the extracellular process, the proteins molecules were extracted from the cells and feasibly interacted with silver ions resulted in Ag NPs (Jena et al., 2014). Similarly, the carbohydrate from another strain, *Scenedesmus* sp. 145-3, was used as an extracellular source for the production of Ag NPs (Patel et al., 2015).

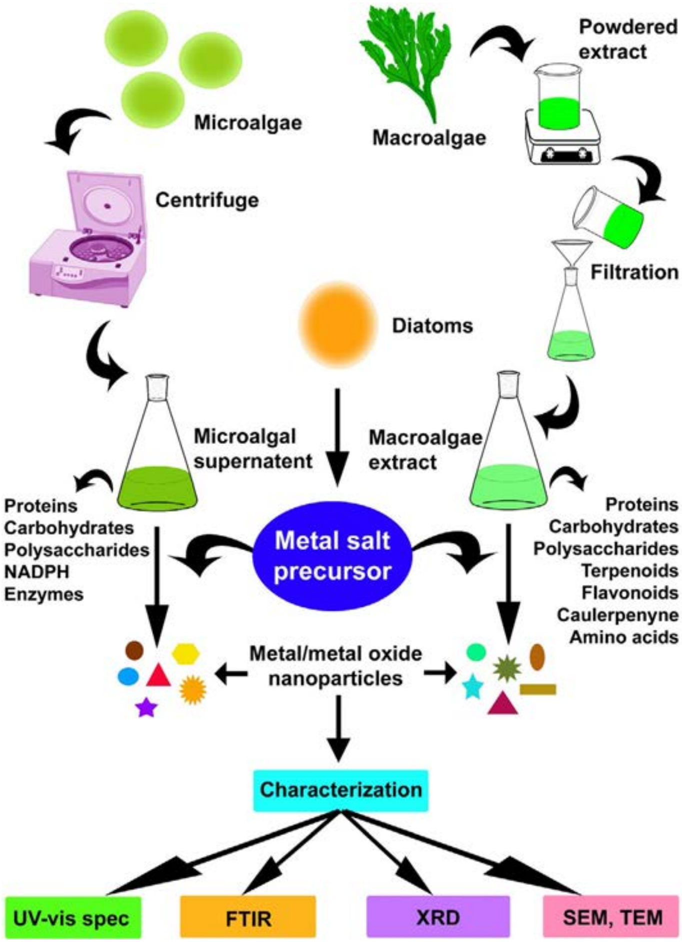

FIG. 2

Synthesis route and characterization of algae-based metal and metal oxide NPs.

Also, Patel et al. (2015) reported the Ag NPs had been synthesized by using algal cultures such as *Coelastrum* sp. 143-1, *Coelastrum* sp. 46-4, *Botryococcus* sp., *Chlorella* sp. 142-5-2, *Chlorella* sp. 2-4, *Chlamydomonas* sp. Ev-29 and *Scenedesmus* sp. Another report by Ebrahiminezhad et al. (2016) to strengthen Patel et al. (2015) study that carbohydrates available in the cell-free supernatant of *Chlorella vulgaris* responsible for the reduction of metallic Ag ions into Ag NPs (Fig. 2). On the other hand, the protein moieties present in the cell-free algal extract of *Chlorella vulgaris* may also a crucial reducing agent involved in the production of Ag NPs (Ebrahiminezhad et al., 2016). Another green microalga, *Acutodesmus dimorphus,* harvested in the dairy effluent actively involved in the fabrication of spherical shaped 2–20 nm-sized Ag NPs (Chokshi et al., 2016). The potency of silver nanoparticles synthesis was examined in three freshwater algae, *Pectinodesmus* sp. HM3, *Dictyosphaerium* sp. HM2 and *Dictyosphaerium* sp. HM1 by Khalid et al. (2017). Herein, the transmission electron microscopic (TEM) observation revealed the synthesized Ag NPs were spherical with a size of about 15–30 nm and 40–50 nm for *Dictyosphaerium* sp. HM1 and *Dictyosphaerium* sp. HM2, respectively. The *Pectinodesmus* sp. HM3 alga achieved a predominantly ovoid shape with 50–65 nm-sized Ag NPs. Interestingly, the exopolysaccharides extracted from *Chlorella pyrenoidosa* and *Botryococcus braunii* acted as reducing and stabilizing candidates in the production of Ag NPs (Gallon et al., 2019) (Fig. 2).

Like Ag NPs, the microalgae are used as an efficient bioreactor to produce gold nanoparticles. While exposing the algae *Tetraselmis kochinensis* to the chloroauric acid solution, the released Au ions from chloroauric acid reduced to Au NPs inside the *Tetraselmis kochinensis* live cell. This critical study was reported by Senapati et al. (2012), and they postulated the reduced gold nanoparticles were highly deposited on the cell wall compared to the cytoplasm. Because the presence of bioactive enzymes in the cell wall of *T. kochinensis* was keenly involved in the reduction of Au ions into Au NPs (Fig. 2). The TEM observations exhibited the dense accumulation of Au NPs in the cell wall, and very few were observed in the cytoplasm region (Senapati et al., 2012). Similarly, Dahoumane et al. (2016) used another microalga *Euglena gracilis* to fabricate Au NPs. They followed a divergent manner to increase Au NPs by altering the growth of *Euglena gracilis*. For that, the microalga was grown in two different conditions, include autotrophic and mixotrophic. Herein, the microalga grown in mixotrophic achieved increased production compared to autotrophic conditions. Interestingly, they have exemplified the lactate in the mixotrophic medium may responsible for the arisen of different shaped Au NPs such as round, hexagonal, triangle, pentagonal, and truncated triangles. The same concept is that through scanning electron microscopy (SEM), the Au NPs were observed mostly in the cell surface region, and the least amount was spotted inside the cell. In addition, observation of a few particles beneath the cell surface indicated the release of NPs from the cells. From the results, they postulated that the spherical shaped NPs were predominantly observed inside the cell. However, the different shaped Au NPs observed in TEM analysis may contribute to the shape-tuned extracellular synthesis of Au NPs by the associating discharged bioactive molecules of lactate lysed cells in the medium (mixotrophic). The cell lysis possibly occurred by the increased concentration of Au(III) ions in the lactate medium (Dahoumane et al., 2016). The report of Yin et al. (2010) also provided appropriate evidence that the lactate molecules' capability as a reducing agent and possibly responsible for the growth of different shapes Au NPs. An interesting report by Shakibaie et al. (2010) stated the extracellular fabrication of Au NPs by using the extract of microalga *Tetraselmis suecica* cells. The extract from disrupted cells was used as an efficacious source for the apparition of Au NPs. The TEM observation significantly revealed spherical shaped Au NPs with an average particle size of about 79 nm. Also, compared to previous results related to algal mediated Au NPs synthesis, Shakibaie et al. (2010) have taken a very low incubation period (5 min) to synthesize Au NPs.

The palladium (Pd) NPs are also the critical NPs mostly used for photocatalytic and antimicrobial studies. Eroglu et al. (2013) used the *Chlorella vulgaris* to synthesis Pd NPs from an aqueous solution of sodium tetrachloropalladate. The TEM observations stated the size of the synthesized Pd NPs were in the range of 2–15 nm. Herein, interestingly, they have found that the cofactor nicotinamide adenine dinucleotide phosphate (NADPH) in *C. vulgaris* possibly involved in the reduction of Pd(II) into Pd NPs (Fig. 2). Similarly, the *C. vulgaris* was utilized by another group Arsiya et al. (2017), for the production of Pd NPs from palladium chloride ($PdCl_2$). They have observed that the *C. vulgaris* extract has taken 10 min only to synthesis Pd NPs from $PdCl_2$. Through Fourier Transform Infrared Spectroscopy analysis (FTIR), they concluded that amide and polyol functional groups in the phytochemicals or biomolecules of *C. vulgaris* extract might be possible responsible reducing agents involved in the reduction of $PdCl_2$ into Pd NPs (Arsiya et al., 2017). *Botryococcus braunii,* one of the green algae, was employed to synthesis Pd and platinum (Pt) NPs by Arya et al. (2020). The SEM images clearly showed the synthesized Pd and Pt NPs average size of about 4.89 and 86.96 nm, respectively. Besides, they concluded the hydroxyl groups in fatty acids, polysaccharides, and proteins of *B. braunii* algal extract might be strongly intermingled with synthesized Pd and Pt NPs. Therefore, these biomolecules might be possible reducing/stabilizing agents in the NP synthesis process.

Subramaniyam et al. (2015) have developed a phyco-based manufacturing unit using *Chlorococcum* sp.MM11 for the production of iron (Fe) NPs. This green nano factory efficiently synthesized spherical Fe NPs with the size ranges of 20–50 nm. In addition, the TEM observations exhibited the Fe NPs mostly deposited on the surface of *Chlorococcum* sp.MM11 cells due to the presence of glycoproteins and polysaccharides. Moreover, they pointed out the amide and carbonyl groups of *Chlorococcum* sp.MM11 biomolecules might be acting as reducing and capping agents (Subramaniyam et al., 2015). The green microalgae *B. braunii* is potentially used as an acceptable source for copper (Cu) NPs. The synthesized Cu NPs hold an average particle size of about 58 nm, and possibly the biomolecules such as polysaccharides, proteins, fatty acids, and amides were involved in the Cu NPs reduction and stabilization process (Arya et al., 2018).

4.2 Metal oxide NPs

Microalgae also act as effective excellent power reactors for the production of metal oxide NPs. Like metal NPs (Ag, Au, Pd, and Fe), the metal oxide NPs such as zinc oxide (ZnO), titanium dioxide (TiO_2), and copper oxide (CuO) NPs are also exhibited potent biological activities. Therefore, the synthesis of metal oxide NPs is also one of the prominent arenas required to empower and fascinating their nanomedicine applications. Limited reports are available to prove the metal oxide NPs synthesis ability of microalgae. *Chlamydomonas reinhardtii,* the microalga usually growing in freshwater, was potentially used as a superb bioreactor for the production of ZnO nanoflowers. Here, the *C. reinhardtii* cell-free extract effectively reduces the zinc acetate dehydrate into ZnO nanorods (NRs). Further, the NRs are aggregated to form a flower-like structure. The proteins biomolecules present in the extract of *C. reinhardtii* cell might be responsible for stabilizing as-synthesized ZnO NRs (Rao and Gautam, 2016). Zhang et al. (2019) used the extract of *C. vulgaris* to synthesis ZnO NPs. The rich protein moieties of *C. vulgaris* energetically involved in the synthesis of 20–40 nm sized ZnO NPs. Similarly, Khalafi et al. (2019) have taken the *Chlorella* powder extract to synthesis ZnO NPs. They have postulated that the presence of proteins, carbohydrates, peptides, fiber, and vitamins might be involved in both the reduction and stabilization of synthesized ZnO NPs. Due to these biomolecules' presence; they have produced ZnO NPs with an average size of about 20 nm. Another group Taghizadeh et al. (2020), utilizes the carbohydrate waste of *C. vulgaris* to produce ZnO NRs. During bulk culturing of *C. vulgaris*, it can produce the carbohydrates that are the waste byproducts that have been used as a nano-green factory for the synthesis of ZnO NRs. These carbohydrates acted as a growth controlling agent to fabricate the ZnO in the form of NRs.

Sharma et al. (2018) documented that the extract of *Chlorella pyrenoidosa* has the ability to synthesis TiO_2 NPs. The SEM analysis exhibited the synthesized TiO_2 NPs were in spherical with a diameter of 50 nm. Similarly, Bhattacharya et al. (2019) examined the CuO NPs synthesis capability of a powdered extract of *Anabaena cylindrical* microalgae. The biological substances such as polysaccharides, terpenoids, and flavones of *A. cylindrical* algal extract play a remarkable role as both reducing and capping molecules in the CuO NPs production. Moreover, they hypothesized the synthesized CuO NPs size was significantly less of about 3.6 nm during high centrifugal speed (900 rpm) compared to particles (42.54 nm) obtained at low centrifugal speed (500 rpm). The centrifugal speed is one of the prominent factors to restrict the size of the NPs. During high centrifugal speed, the synthesized NPs were broken down into fine tiny particles (Bhattacharya et al., 2019).

5 Nanoparticles synthesized by macroalgae

5.1 Metal NPs

Like microalgae, the macroalgae is also primarily involved in the production of Ag and Au NPs. Brown algae *Sargassum wightii* was effectively used as a potential source for the fabrication of silver nanoparticles by Govindaraju et al. (2009). They exemplified the conversion of –OH (alcoholic) to –CHO (aldehyde) through oxidation, and it might have resulted in the reduction of Ag metal ions from silver nitrate salt into Ag NPs (Fig. 3). The TEM observations showed the manufactured Ag NPs were mostly spherical and size in the range of 8–27 nm. Prasad et al. (2013) have used marine brown algae *Cystophora moniliformis* to synthesize of Ag NPs. They have concluded that the temperature is one of the key parameters to determine the size of the synthesized Ag NPs. Because they have synthesized Ag NPs in two different temperatures was 65°C and 95°C. In 65°C, the SEM observations exhibited that the average size of the produced Ag NPs was about 75 nm. However, at 95°C,

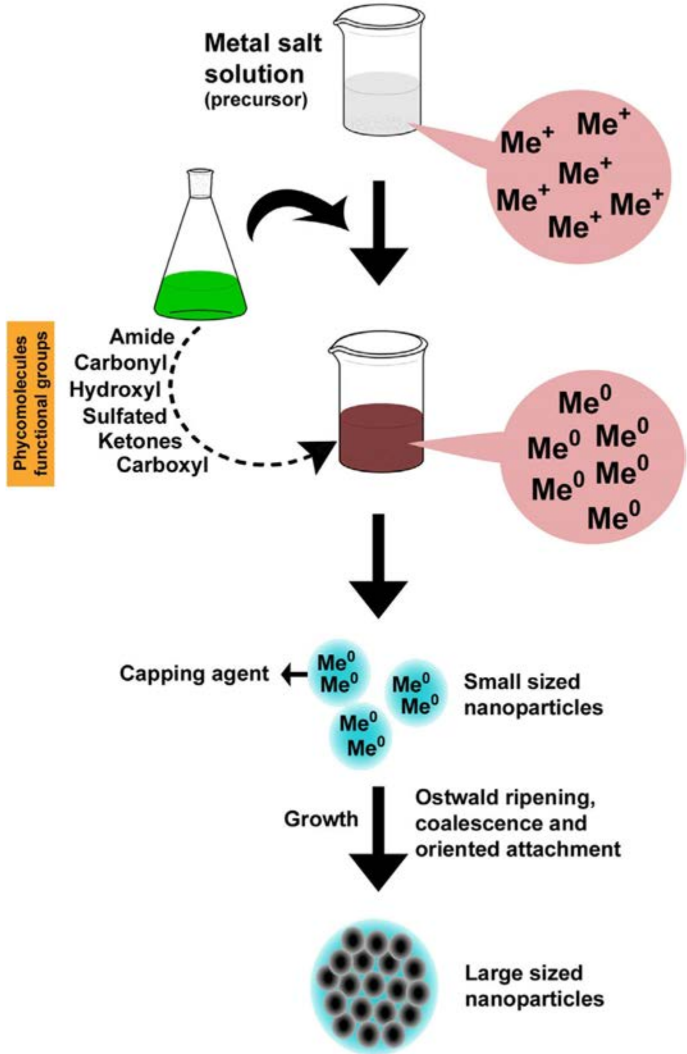

FIG. 3

Possible involvements of phycomolecules in production of NPs.

the average size of fabricated Ag NPs was more than 2 μm. During high temperatures, the synthesized NPs were aggregated and resulted in large-sized NPs (Prasad et al., 2013). The Ag NPs synthesis potency was examined in another brown alga, *Sargassum polycystum* by Palanisamy et al. (2017). The results concluded that the synthesized Ag NPs were spherical, and the amides groups of *S. polycystum* proteins responsible for the capping of Ag NPs.

The extract of marine green algae *Caulerpa serrulata* is actively used as a biological green manufacturing unit to produce Ag NPs (Aboelfetoh et al., 2017). But, this report is controversial compared to the result of Prasad et al. (2013) that high temperature (95°C) revealed the synthesis of nano-sized Ag NPs of about 10 nm. At low temperature (27°C), a weak surface plasmon resonance (SPR) peak was observed 440 nm in the UV-vis spectrum. However, the higher temperature (95°C) exhibited a sharp, intense SPR peak at 412 nm, resulting in the production of smaller sized Ag NPs. Recently, another controversial report by Liu et al. (2020) stated the size of Ag NPs increases with increasing the temperature from 70°C (7.8 ± 2.3 nm) to 90°C (17.6 ± 4.5 nm). Therefore, a huge unsolved qualm has raised whether the temperature increases or decreases the size of the NPs. Except for the temperature, other parameters such as pH, metal ion (precursor) concentration, reducing agent concentration, and reaction time also possibly affect the size and morphology of the NPs (Khan et al., 2019). Probably there are two ways involved in the growth of NPs include Ostwald ripening and oriented attachment. In Ostwald ripening, the reduced atoms are aggregated to form large-sized NPs. But the oriented attachment process defines the growth of large-sized NPs because of the aggregation of synthesized small-sized NPs. Hence, the size of the NPs may be related to the temperature on NPs growth (i.e.) during Ostwald ripening and oriented attachment (Madras and McCoy, 2003; Xue et al., 2014) (Fig. 3).

Fatima et al. (2020) examined the Ag NPs synthesis property on medicinally potent *Portieria hornemannii*, red algae obtained from the Gulf of Mannar, Rameshwaram, India. Actually, in this study, the Ag^+ ions have taken only 60 min to complete the reduction of Ag metal ions into Ag NPs. Similarly, *Gelidium corneum*, another red alga, has undergone the production of Ag NPs. The red algae extract employed as a reducing agent to synthesis Ag NPs with the size ranges from 20 to 50 nm. The FTIR analysis revealed the aldehyde group oxidation and the presence of azo-based compounds might be possible functional groups involved in the fabrication of Ag NPs (Ozturk et al., 2020).

Apart from proteins and fatty acids, the medicinally valuable sulfated polysaccharides in the macroalgae play a remarkable role in the production of NPs. Fucoidan is present in marine brown algae actively participating in reducing metal ions into metal NPs (Fig. 2). For instance, fucoidan extracted from the marine algae *Spatoglossum asperum* used to synthesis spherical shape with the size ranges between 20 and 46 nm. The results concluded that the sulfate and aromatic compounds effectively contributed to the bioreduction of ionic Ag to Ag NPs (Ravichandran et al., 2018). Another report brought additional evidence that polysaccharides, including fucoidan, alginate, and laminarin extracted from marine macroalgae *Fucus evanescens* and *Saccharina cichorioides,* also potentially involved in the fabrication of Ag NPs. But the report concluded the alginate from *F. evanescens* expressed increased Ag metal ion reduction compared to fucoidan isolated from both algae and laminarin. The XRD analysis revealed the average particle size for alginate of about 18 nm was smaller compared to laminaran (29 nm), fucoidan from *F. evanescens* (24 nm), and fucoidan (37 nm) from *S. cichorioides*. In the ionic Ag reduction process, these different polysaccharides acted to reduce and stabilize candidates (Yugay et al., 2020).

The Au NPs are also promising agents filled with various biological activities such as antimicrobial, anticancer, antidiabetic, antitumor, and anti-inflammatory (Patil and Kim, 2017; Guo et al., 2020; Muthukumar et al., 2016; Singh et al., 2018). *S. wightii* is one the marine source has potential involvement in the production of monodispersed Au NPs. The size obtained Au NPs from *S. wightii* of about 8 to 12 nm. They suggested that the polysaccharides present in the extracellular of *S. wightii* might be acting as a possible stabilizing agent to achieve monodispersed Au NPs (Singaravelu et al., 2007). *Stoechospermum marginatum,* another marine brown alga, collected by Rajathi et al. (2012) from coastal area Tuticorin, India, explored the Au NPs production's potency. The recovered Au NPs from *S. marginatum* biomass hold specific shapes such as spherical, triangle, and hexagonal with a size range of 18.7–93.7 nm. The XRD pattern indicated that the appearance of additional peaks with standard Au peaks might be the occurrence of biological moieties of *S. marginatum* associated with synthesized Au NPs. It is a usual matter in biological protocols, and the association these phytochemical constituents of biomolecules was removed by repeated centrifugation of NPs solution with deionized water (Rajathi et al., 2012). Similarly, Venkatesan et al. (2014) have taken *Ecklonia cava* to check the efficacy of Au NPs production. Impressively, the powdered algal extract was taken only 60 s to complete the formation of Au NPs at the reaction temperature of 80°C. The average size of algal extracts synthesized Au NPs was 30 ± 0.25 nm with triangle and spherical shapes. In contrast, a small size of about 8.4 ± 2.2 nm Au NPs was synthesized by the extract of *Cystoseira baccata* (Gonzalez-Ballesteros et al., 2017). The polysaccharides, such as fucoidans and polyphenols, acted as a barrier system to avoid the coalescence and aggregation of synthesized Au NPs (Gonzalez-Ballesteros et al., 2017; Yugay et al., 2020). Similarly, Colin et al. (2018) found that the powdered extract of *Egregia* sp. also can produce Au NPs with a size of about 8 nm. Prior, they have taken different dilution concentration of algal powder extract of 0.025 to 9.0 mg/mL for the production of Au NPs. Finally, the optimized concentration of 2.5 mg/mL of powdered algal extract is appropriate for fabricating small-sized Au NPs. The biologically active algal extract molecules effectively played as reducing agents for reducing aqueous Au ions into Au NPs. Additionally, these biomolecules offered a bio-fence to protect synthesized colloidal Au NPs from aggregation (Colin et al., 2018). The green alga *Caulerpa racemosa* was undergone Au NPs production by interacting with chloroauric acid (Manikandakrishnan et al., 2019). Generally, the formation of Au NPs was primarily identified by the formation of Ruby red color (Kumar et al., 2011). For Ag NPs, the mostly brown color appeared to confirm Ag NPs in the reaction mixture (aqueous silver nitrate with plant extract) (Kumar et al., 2014). The color changes were occurred by the oscillation of electrons of the surface of NPs or the excitation of surface plasmon resonance in synthesized NPs (Mulvaney, 1996; Petryayeva and Krull, 2011). The obtained Au NPs size was in the range of 13.7–85.4 nm with spherical and oval shapes. The proteins of *C. racemosa* might be acted as a capping agent in the production of Au NPs (Manikandakrishnan et al., 2019). Similarly, the red alga

Galaxaura elongate also actively participated in the fabrication of Au NPs through the interaction with aqueous chloroauric acid. The aqueous powdered algal extract has taken 3 h to initiate the synthesis of Au NPs, whereas the ethanolic algal extract has taken 2 to 5 min to produce the Au NPs. The phytochemical constituents such as epicatechin gallate, gallic acid, stearic acid, alloaromadendrene oxide, oleic acid, glutamic acid, etc. have mostly extracted from *G. elongate* through ethanol solvent. Moreover, these molecules are plausibly responsible for various processes, including reduction, stabilization, and capping (Abdel-Raouf et al., 2017). Like green alga *C. racemosa* (Manikandakrishnan et al., 2019), the *G. elongate* red alga produced Au NPs size of 3.85 to 77.13 nm with shapes like spherical, triangle, hexagonal, and truncated triangle (Abdel-Raouf et al., 2017). Recently, the alga *Saccharina japonica* has been used to synthesize different size Au NPs of about 72 nm and 10 nm by changing the algal extract concentrations. The 1 mL volume of algal extract reacts with aqueous gold chloride trihydrate to obtain 72 nm large sized Au NPs. Though, increase the volume of algal extract to 2 mL, about 10 nm small-sized Au NPs were produced in the reaction mixture. This algal extract also completed the Au NPs formation process in 20 min (2 mL algal extract) and 40 min (1 mL algal extract) (Khoshnamvand et al., 2020).

The Pd NPs are also familiarly known for their potent catalytic, adsorption, and antimicrobial activities. *Sargassum bovinum* is one of the algae proficiently participated in the production of Pd NPs. About 5–10 nm-sized nanoparticles were identified by TEM analysis, and further, these NPs were used for catalytic applications (Momeni and Nabipour, 2015). Similarly, Prasad et al. (2015) reported the production of Pd NPs by the dried powdered extract of *S. wightii*. The synthesized NPs were dispersed well in a spherical shape with a size range of 5–37 nm identified by SEM analysis. Likewise, the algae *Ulva lactuca* was involved in the synthesis of selenium (Se) nanoparticles. The Se NPs are an essential micronutrient that plays a pivotal role in therapeutic applications. The polysaccharides xylose, uronic acid, rhamnose, and glucose found in *Ulva lactuca* prominently play a crucial role in the green fabrication of Se NPs (Zhu et al., 2017). Another alga, *Sargassum latifolium* also potentially used for the synthesis of Se NPs. The synthesized spherical shaped Se NPs hold a size of about 22.31–95.16 nm (El-Khateeb et al., 2019). The brown algae *Dictyota dicotoma* undergone divergent iron (Fe) NPs synthesis process, and further, the fabricated Fe NPs were processed to examine its antimicrobial nature (Chandran et al., 2016). The potential phytochemical constituents and biomolecules in algal extracts act as excellent sources for the fabrication of various metal nanoparticles. Further, the involvement of macroalgal extract in the synthesis of metal oxide nanoparticles is discussed in detail in the forthcoming section.

5.2 Production of metal oxide NPs

Like metal NPs, the metal oxide NPs also gained more attraction due to its promising photocatalytic, agriculture, sensor, antimicrobial, anticancer, and antidiabetic activities (Fu and Fu, 2015; Singh et al., 2019; Muthuchamy et al., 2018; Suresh et al., 2018a; Bala et al., 2015). The algae, especially macroalgae are largely used to synthesize metal oxide NPs due to their potent reducing agents (phytochemicals) and eco-friendliness. The powdered extract of *Gracilaria edulis* was efficiently involved in the production of rod-shaped ZnO NPs. The occurrence of quinine in the aqueous extract of algae *G. edulis* might be enrolled as a reducing agent in the production of ZnO NPs. The quinines are high redox potential biomolecules effectively involved in reducing Zn^{2+} from the substrate zinc nitrate to the ZnO NPs (Priyadharshini et al., 2014). The macroalgae are often widely used in food and pharmaceutical industries due to its active biomolecules (McLachlan, 1985; Griffiths et al., 2016). Therefore, the macroalgae are largely used in metal and metal oxide nanoparticle synthesis protocol. Azizi et al. (2014) have taken the macroalgae *Sargassum muticum* to produce hexagonal ZnO NPs, with the size ranges between 30 and 57 nm. Likewise, Pandimurugan and Thambidurai (2016) used the macroalgae *Padina tetrastromatica* for the synthesis of ZnO NPs. Through SEM, they have viewed various-shaped ZnO NPs such as plates, rods, and stars. Herein, they have various Zn substrates such as zinc nitrate, zinc chloride, zinc sulfate, and zinc acetate for the ZnO NPs production. The presence of carboxyl groups in macroalgae's phytochemicals might be effectively associated with the Zn ions and responsible for the various morphological changes of synthesized ZnO NPs. Hence, these functional groups play an essential role in the growth of ZnO NPs. The appearance of elemental Zn from ZnO NPs was higher in zinc acetate substrate than zinc chloride, zinc nitrate, and zinc sulfate (Pandimurugan and Thambidurai, 2016). Another group, Itroutwar et al. (2019), has taken marine brown macroalgae *Turbinaria ornate* to examine the capability to produce ZnO NPs. They have synthesized the ZnO NPs in various shapes, including hexagonal, rod, and spherical, with the size ranges from 15 to 52 nm. The hydroxyl and carboxyl of the macroalgae biomolecules were responsible for reducing and capping synthesized ZnO NPs (Itroutwar et al., 2019). A different and interesting study by Nagarajan and Kuppusamy (2013) that they have used three different macroalgae, *Hypnea valencia* (red algae), *Sargassum myriocystum* (brown algae), and *Caulerpa peltata* (green algae) for the fabrication of nano-sized ZnO. They reported the *S. myriocystum* was actively involved in the synthesis of ZnO NPs compared to *H. valencia* and *C. peltata*. In UV–vis spectroscopic investigation of the ZnO NPs produced by *S. myriocystum* exhibited an SPR peak at 285; in contrast, the ZnO NPs synthesized by *H. valencia,* and *C. peltata* showed no SPR peak in the spectra. Possibly, the effective reducing and capping phytomolecules such as flavonoids, lipids, ascorbic acid, tannins, and alginic acid prevent the aggregation of NPs and might be responsible for the size (36 nm) and shape (hexagonal, spherical, rod, and triangle) controlled ZnO NPs (Nagarajan and Kuppusamy, 2013). Similarly, Ishwarya et al. (2018) have used another *Sargassum* species, *Sargassum wightii,* for the efficient production of ZnO NPs. The uniform spherical shaped ZnO NPs with a size of about 40–50 nm synthesized by *S. wightii*. Another red alga *Gracilaria edulis* has taken into an examination that it can synthesize NPs by reacting with zinc nitrate solution. Expectedly, the algae proficiently synthesis the ZnO NPs, and it was confirmed by the arisen of SPR peak at 367 in the UV-vis spectrum, and the size of about less than 50 nm revealed by TEM analysis. Further, they reported the synthesized rod shaped ZnO NPs hold an efficient cytotoxic activity against cervical cancer cells (Gowdhami et al., 2019).

The MgO NPs are also considerably used in the medicinal field because of its unique properties such as bone regeneration, antibacterial, anticancer, catalysis, and sensor (Pan et al., 2020; Leung et al., 2014; Suresh et al., 2018b; Dobrucka, 2018; Jain et al., 2018). Due to these amazing properties, researchers adversely involved in the synthesis of MgO NPs using non-toxic biological resources. Pugazhendhi et al. (2019) have used the brown algae *S. wightii* to reduce magnesium nitrate into MgO NPs. It is well known that *S. wightii* is rich in phytomolecules such as polyphenols, polysaccharides, and terpenoids. Similarly, the production of MgO NPs by other brown macroalgae *Turbinaria ornata* was reported by Anand et al. (2020). The synthesized MgO NPs were dispersed as clusters with an average grain size of about 12 nm. The same algae *T. ornate* were utilized to manufacture magnesium hydroxide (MgOH) NPs documented by Govindaraju et al. (2020). The MgOH NPs were in nanoflakes' morphology with the dimension and thickness of about 16.29 nm and 7.75 nm, respectively. Further, they have proved the MgOH NPs have remarkable bactericidal activity against *Mycobacterium tuberculosis*.

The iron oxide (FeO) NPs also has excellent adsorption and photocatalytic properties (Khaleelullah et al., 2017; Vasantharaj et al., 2019) and additionally, the superparamagnetic features of FeO NPs expressed its proficient application in cancer diagnosis and therapy (Yigit et al., 2012). Two marine macroalgae, namely, *Sargassum acinarium* and *Padina pavonica*, effectively reduce ferric chloride into FeO NPs. The sulfur attached polysaccharides play a talented role in the synthesis of FeO NPs as reducing and stabilizing candidates (El-Kassas et al., 2016). Similarly, another *Sargassum* species, *Sargassum muticum* employed to manufacture FeO NPs through the reduction of ferric chloride hexahydrate. Here, the polysaccharides containing sulfur groups are proficiently involved in the reduction and the stabilization process (Mahdavi et al., 2013). Khaleelullah et al. (2017) performed a divergent protocol to synthesis FeO NPs through the addition of powdered *Turbinaria decurrens* extract to the aqueous solution containing both ferric chloride (II) tetrahydrate and ferric (III) chloride hexahydrate. The fabricated FeO NPs derived the average size of about 18 nm, and further, they have used the NPs for the dye degradation applications. Salem et al. (2019) also performed the FeO NPs synthesis process using two different marine macroalgae *Pterocladia capillacea* (red algae) and *Colpomenia sinuosa* (brown algae). The same ferric chloride has been taken by the Salem et al. (2019) for FeO NPs production and obtained the size range of 16 to 23 nm for *P. capillacea* and 11 to 34 for *C. sinuosa*, respectively.

The CuO NPs are also widely synthesized by green procedures due to their broad-spectrum antibacterial activities (Sivaraj et al., 2014). The marine brown algae *Bifurcaria bifurcate* was employed to synthesis CuO NPs from the reduction of aqueous copper (II) sulfate solution. The produced CuO NPs carried a size of about 5 to 45 nm, and diterpenoids of *B. bifurcate* is mainly responsible for reducing and stabilizing process (Abboud et al., 2014). Similarly, another brown macroalga, *Sargassum polycystum* was also undergone CuO NPs synthesis through the involvement with copper sulfate solution. The synthesized CuO NPs exhibited its potent cytotoxicity effect against bacterial, fungal, and cancer cells (Ramaswamy et al., 2016). The *Dictyota indica* is one of the brown algae potentially used as an excellent green biosource to fabricate palladium oxide (PdO) NPs. The spherical shaped and 19 nm-sized PdO NPs showed a remarkable application in removing toxic cadmium metals from the water (Yazdani et al., 2018). Similarly, aluminum oxide (AlO) NPs were synthesized by the green protocol using the powdered extract of *Sargassum ilicifolium*. The algae's biomolecules are responsible for producing spherical and 20 nm-sized AlO NPs (Koopi and Buazar, 2018). In addition, the zirconium oxide (ZrO) NPs was also a strong antibacterial agent synthesized by *S. wightii* through its efficient biomolecules. The monodispersed spherical shaped NPs with an average mean size of 5 nm obtained from algal extract (Kumaresan et al., 2018).

Therefore, the different algal species reacted with various substrate molecules to produce noble metal and metal oxide NPs because of their divergent applications in various fields. Moreover, algal species' green procedure is unique, toxic chemical-free and eco-friendly nature could be the excellent bio-factories for safety production of different NPs. The factors such as metal/metal oxide concentration, reducing/stabilizing/capping agent (algal extract concentration), incubation time, temperature and pH are important to determine the size and shape of the NPs (Patra and Baek, 2014; Tran et al., 2016; Chelli and Golder, 2016; Ovais et al., 2018a). We can tune the NPs morphology and size for the desired catalytic/sensor/biological applications by changing these factors.

6 Possible mechanism

According to biological synthesis protocol, numerous reports are available to explain the possible mechanisms involved in NPs synthesis, but the detail and exact process remain unclear. In microbe mediated process, enzymes/proteins including NADH and NADPH dependent enzymes, glucosidase, nitrate reductase, sulfate reductase, and beta-glucosidase acts as a prominent key role in the reduction/stabilization of NPs (Ahmad et al., 2002; Senapati et al., 2005; Ovais et al., 2018a,b; El-Seedi et al., 2019). In plants, several phytochemicals such as phenols, flavonoids, terpenoids, alkaloids, organic acids, and pigments play a proficient role in synthesizing nanoparticles (Ovais et al., 2018b). In plant-mediated synthesis, the algal resources are widely used by the researchers to synthesize metal and metal oxide NPs successfully. Generally, the algae are rich in various phytochemicals, including proteins, carbohydrates, polysaccharides, peptides, terpenoids, flavonoids, and amino acids (Fig. 2). The functional groups of these biomolecules such as carboxyl, hydroxyl, amide, ketones, amine, and sulfonic groups actively participate in the reduction and stabilization of synthesized NPs (Khanna et al., 2019) (Table 1).

It is well known that algal species can grow in the heavy metal contaminated water resources. The algae uptakes the heavy metals and converting them into active nutrients and used it for their growth (Abdel-Raouf et al., 2012; Shanab et al., 2012).

Table 1 Involvement of various biomolecules and functional groups in NPs production.

S. No.	Algae	Biomolecules	Functional groups	Process	NP	References
Microalgae						
1	*Acutodesmus dimorphus*	Proteins	Amide linkage	Reduction/Stabilization	Ag	Chokshi et al. (2016)
2	*Chlorella vulgaris*	Carbohydrates	Hydroxyl, carboxylic, phenolic and carbonyl	Reduction/Stabilization	Ag	Ebrahiminezhad et al. (2016)
3	*Scenedesmus sp.*	Proteins	Hydroxyl	Reduction/Stabilization	Ag	Jena et al. (2014)
4	*Botryococcus braunii*	Exopolysaccharides	Hydroxyl and carboxyl	Reduction/Stabilization	Ag	Gallon et al. (2019)
5	*Chlorella pyrenoidosa*	Exopolysaccharides	Hydroxyl and carboxyl	Reduction/Stabilization	Ag	Gallon et al. (2019)
6	*Dictyosphaerium* sp. strain HM2	Biomolecules	Primary alcohols and alkanes	Reduction/Stabilization/ Capping	Ag	Khalid et al. (2017)
7	*Pectinodesmus* sp. strain HM3	Biomolecules	Primary amines and aldehydes	Reduction/Capping	Ag	Khalid et al. (2017)
8	*Chlorococcum sp.* MM11	Polysaccharides and glycoproteins	Carbonyl and amide	Reduction/Capping	Fe	Subramaniyam et al. (2015)
9	*Chlorella vulgaris*	Biomolecules	Polyol and amide	Reduction/Capping	Pt	Arsiya et al. (2017)
10	*Chlorella vulgaris*	Proteins	Carboxylate, cysteine and amine	Reduction/Capping	Ag	Annamalai and Nallamuthu (2016)
11	*Chlorella vulgaris*	Proteins, phenols and flavonoids	Amide	Reduction/Capping	Au	Annamalai and Nallamuthu (2015)
12	*Chlorella vulgaris*	Cofactor- NADPH	–	Reduction	Pd	Eroglu et al. (2013)
13	*Chlamydomonas reinhardtii*	Proteins	Amide	Reduction/Stabilization/ Capping	ZnO	Rao and Gautam (2016)
14	*Chlorella*	Carbohydrate	Hydroxyl	Reduction	ZnO	Khalifa et al. (2016)
15	*Anabaena cylindrica*	Terpenoids, flavones and polysaccharides	C–O bond	Reduction/Capping	CuO	Bhattacharya et al. (2019)
16	*Botryococcus braunii*	Proteins and polysaccharide	Hydroxyl	Reduction/Stabilization/ Capping	Cu and Ag	Arya et al. (2018)
Macroalgae						
17	*Sargassum wightii*	Biomolecules	Carboxylate ions	Reduction	ZrO	Kumaresan et al. (2018)
18	*Sargassum muticum*	Polysaccharide	Sulfated, carboxyl, amino, and hydroxyl	Stabilization	ZnO	Azizi et al. (2014)

19	*Ulva faciata, Jania rubins*, *Colpmenia sinusa*, and *Pterocladia capillacae*	Proteins and polysaccharide	Carbonyl, amide and hydroxyl	Reduction/Stabilization	Ag	El-Rafie et al. (2013)
20	*Sargassum Alga*	Sulfated polysaccharide	Sulfated and hydroxyl	Reduction/Capping	Pd	Momeni and Nabipour (2015)
21	*Bifurcaria bifurcata*	Diterpenoids	Unsaturated ketones	Reduction/Stabilization	CuO	Abboud et al. (2014)
22	*Saccharina cichorioides* and *Fucus evanescens*	Laminaran, alginate and fucoidan	Hydroxyl and amine	Reduction/Stabilization	Ag	Yugay et al. (2020)
23	*Caulerpa serrulata*	Caulerpenyne and their derivatives	–	Reduction/Stabilization	Ag	Aboelfetoh et al. (2017)
24	*Spatoglossum asperum*	Fucoidan	C–C stretching of aromatic compounds and sulfated groups	Reduction/Stabilization	Ag	Ravichandran et al. (2018)
25	*Portieria hornemannii*	Proteins/amino acids	Carbonyl	Reduction/Stabilization	Ag	Fatima et al. (2020)
26	*Gelidium corneum*	Biomolecules	Aldehyde and azo compounds	Reduction/Stabilization	Ag	Ozturk et al. (2020)
27	*Cystoseirabaccata*	Polysaccharide	Sulfonic group	Reduction	Au	Gonzalez-Ballesteros et al. (2017)
28	*Caulerpa racemosa*	Proteins	Amide and carboxylic acid	Reduction/Capping	Au	Manikandakrishnan et al. (2019)
29	*Stoechospermum marginatum*	Terpenoids	Hydroxyl	Reduction	Au	Rajathi et al. (2012)
30	*Ecklonia cava*	Biomolecules	Primary amine and hydroxyl	Reduction/Stabilization	Au	Venkatesan et al. (2014)
31	*Galaxaura elongata*	Amino acids and peptides	Carbonyl	Reduction/Capping	Au	Abdel-Raouf et al. (2017)
32	*Saccharina japonica*	Glycine, lysine, valine, aspartic acid and glutamic acid	–	Reduction/Stabilization	Au	Khoshnamvand et al. (2020)

Moreover, it can convert inorganic and organic wastes into reliable fuels and bioenergy (Abdel-Raouf et al., 2012; Souza et al., 2012; Piccini et al., 2019). Due to the availability of the phycomolecules as mentioned earlier and other biomolecules, the algae effectively degrade the toxic heavy metal and dyes. For instance, the mercury (Hg) of acutely toxic chemicals causes adverse effects on aquatic organisms and humans. These hazardous Hg^+ ions from $HgCl_2$ were reduced to malleable Hg^0 and beta HgS through the microalgae's enzymatic reaction (Kelly et al., 2007). Similarly, the noxious arsenic (V) also converted arsenic (III) and subsequently to methylated arsenic species through the methylation process by the marine diatoms (Papry et al., 2019). Therefore, based on the concept of phycoremedition, the micro, and macroalgae subjected to the production of metal and metal oxide NPs. The reduction/oxidation (redox) of phytochemicals/biomolecules in the algal extract is the basic phenomenon involved in the synthesis of NPs (Khanna et al., 2019). Interestingly, Eroglu et al. (2013) demonstrated that the NADPH is an important reducing capability cofactor that donates the electrons and reduces Pd(II) ions into Pd NPs.

The nucleation and growth of NPs in the algal medium as follows, initially, in aqueous solution, the metal ions (Me^+) were nucleated from metal salts, and subsequently, the Me^+ ions were converted to Me^0 through redox of phycomolecules. Further, the growth of Me^0 was attributed by Ostwald ripening, coalescence, and oriented attachment to produce small and large-sized Me NPs (Madras and McCoy, 2003; Xue et al., 2014; Khanna et al., 2019) (Fig. 3). The growth and aggregation of metal and metal oxide NPs depended on the availability of reducing and capping agents. These are the important factors to control the size and shape of synthesized NPs.

7 Diatoms

Both fresh and marine water diatoms successfully participated in the fabrication of metal NPs. The freshwater habitat diatom *Navicula* actively reacted with silver nitrate and produced Ag NPs. The hydroxyl groups in proteins moieties of diatoms acted as a reducing agent in the synthesis of Ag NPs (Chetia et al., 2017). The fucoxanthin pigment responsible for phytosynthesis in *Amphora* sp. diatom was performed as a reducing agent in reducing Ag metal ions to Ah NPs. The obtained Ag NPs with a size range of 20 to 25 nm showed its adverse cytotoxic effect against Gram-positive and Gram-negative bacteria (Jena et al., 2015). Similarly, the freshwater diatom *Eolimna minima* actively participated with the potassium gold (III) chloride and synthesis Au NPs (Feurtet-Mazel et al., 2016). Further, the Au NPs were also prepared using marine water *Stephanopyxis turris* diatom, as reported by Pytlik et al. (2017). However, the bioreduction mechanism of Au ions to Au NPs was not clearly explained in the report of Pytlik et al. (2017). But, Borase et al. (2017) demonstrated the development of Au NPs by the diatom *Nitzschia* through its bio/phytomolecules such as proteins and carbohydrates. The biomolecules possibly acted as reducing as well as stabilizing agents in the fabrication of Au NPs. The diatoms manufactured

Ag and Au NPs are potentially used in sensing and antibacterial applications (Chetia et al., 2017; Jena et al., 2015).

8 Future outlook

Recently, the green synthesis procedure is a fine and excellent alternative process for the classical NPs synthesis protocol. Hence, the microorganism and plant materials are considered as potential sources to produce NPs. Amid, the algae materials are serving its promising positive impacts on the green synthesis of the NPs process due to its remarkable phycomolecules. The phytochemicals and other biomolecules present in the algae possess an excellent biological activity, including antimicrobial, anticancer and it serving as notable biofertilizer for increased crop production. Nowadays, focused research is ongoing to synthesis NPs with multifunctional properties. For instance, NPs used in the wastewater system may activate against the toxic heavy metals, dyes, and microorganisms. Hence, it is important to fabricate the NPs with these salient characteristic features and fewer side effects. Therefore, the fabrication of these algal phytochemicals (AP) in nanosized forms (N-AP) through novel technologies and along with metal/metal oxide NPs (N-AP-M/MO), this N-AP-M/MO may result in enhanced activity and push the algae combined NPs with widespread applications in all fields. The non-toxic and biocompatibility of algae-based NPs could be useful in biomedical applications, especially in bioimaging and cancer diagnosis. Therefore, the NPs synthesized from algae will open an era to explore new findings for threatening diseases in medicine with appropriate strategies. In the future, it will expand the scientific knowledge of novel and innovative nano-based technologies to another level for our next generation.

9 Conclusion

Recently, the synthesis of metal and metal oxide NPs by green factories attained fascinating attention due to its non-toxic, rapid, cost-effective, and eco-friendly manner. These all features are fulfilled by the algae materials and provide an alternative process for the production of NPs. The cultivation of algae is facile, and according to cost, it is so cheap which makes them large in NPs production. The different parameters such as pH, temperature, metal ion concentration, etc. are employed in the synthesis process to obtain size and shape-controlled NPs. These NPs are opening a promising scientific evolution in medicine, pharmaceuticals, diagnosis, agriculture, cosmetics, and food technology. Nowadays, most material synthesis researchers struggle to find newly biocompatible and cheap greener approaches to synthesize NPs without affecting the environment. However, the NPs synthesis mechanism is still not cleared, and few researchers exemplify the possible phycomolecules involved in the fabrication of NPs. Further, the release of NPs from various industries is also considered a huge challengeable concern, and escaping from the adverse effects of NPs is a complicated task to protect the aquatic and terrestrial eco-system. Therefore, scientists have to tune the synthesis protocol to obtain non-toxic desired NPs for appropriate applications. This chapter concluded the algal materials are professional greener factories to synthesis metal and metal NPs. In the future, the algae mediated NPs will open a novel scientific evolution through its fabulous performance in various industrial, medicinal, and agricultural applications.

Acknowledgments

Authors thank biorender and presentation go for making drawing in this chapter.

References

Abbasi, E., Milani, M., Fekri Aval, S., Kouhi, M., Akbarzadeh, A., Tayefi Nasrabadi, H., Nikasa, P., Joo, S.W., Hanifehpour, Y., Nejati-Koshki, K., Samiei, M., 2016. Silver nanoparticles: synthesis methods, bio-applications and properties. Crit. Rev. Microbiol. 2, 173–180.

Abboud, Y., Saffaj, T., Chagraoui, A., El Bouari, A., Brouzi, K., Tanane, O., Ihssane, B., 2014. Biosynthesis, characterization and antimicrobial activity of copper oxide nanoparticles (CONPs) produced using brown alga extract (*Bifurcaria bifurcata*). Appl. Nanosci. 4, 571–576.

Abdel-Raouf, N., Al-Homaidan, A.A., Ibraheem, I.B.M., 2012. Microalgae and wastewater treatment. Saudi J. Biol. Sci. 19, 257–275.

Abdel-Raouf, N., Al-Enazi, N.M., Ibraheem, I.B., 2017. Green biosynthesis of gold nanoparticles using *Galaxaura elongata* and characterization of their antibacterial activity. Arab. J. Chem. 10, 3029–3039.

Aboelfetoh, E.F., El-Shenody, R.A., Ghobara, M.M., 2017. Eco-friendly synthesis of silver nanoparticles using green algae (*Caulerpa serrulata*): reaction optimization, catalytic and antibacterial activities. Environ. Monit. Assess. 189, 349.

Ahmad, A., Mukherjee, P., Mandal, D., Senapati, S., Khan, M.I., Kumar, R., Sastry, M., 2002. Enzyme mediated extracellular synthesis of CdS nanoparticles by the fungus, *Fusarium oxysporum*. J. Am. Chem. Soc. 124, 12108–12109.

Anand, K.V., Anugraga, A.R., Kannan, M., Singaravelu, G., Govindaraju, K., 2020. Bio-engineered magnesium oxide nanoparticles as nano-priming agent for enhancing seed germination and seedling vigour of green gram (*Vigna radiata* L.). Mater. Lett. 271, 127792.

Annamalai, J., Nallamuthu, T., 2015. Characterization of biosynthesized gold nanoparticles from aqueous extract of *Chlorella vulgaris* and their anti-pathogenic properties. Appl. Nanosci. 5, 603–607.

Annamalai, J., Nallamuthu, T., 2016. Green synthesis of silver nanoparticles: characterization and determination of antibacterial potency. Appl. Nanosci. 6, 259–265.

Arsiya, F., Sayadi, M.H., Sobhani, S., 2017. Green synthesis of palladium nanoparticles using *Chlorella vulgaris*. Mater. Lett. 186, 113–115.

Arya, A., Gupta, K., Chundawat, T.S., Vaya, D., 2018. Biogenic synthesis of copper and silver nanoparticles using green alga *Botryococcus braunii* and its antimicrobial activity. Bioinorg. Chem. Appl. 2018. https://doi.org/10.1155/2018/7879403.

Arya, A., Gupta, K., Chundawat, T.S., 2020. *In-vitro* antimicrobial and antioxidant activity of biogenically synthesized palladium and platinum nanoparticles using *Botryococcus braunii*. Turk. J. Pharm. Sci. 17, 299.

Aziz, N., Faraz, M., Pandey, R., Shakir, M., Fatma, T., Varma, A., Barman, I., Prasad, R., 2015. Facile algae-derived route to biogenic silver nanoparticles: synthesis, antibacterial, and photocatalytic properties. Langmuir 31, 11605–11612.

Azizi, S., Ahmad, M.B., Namvar, F., Mohamad, R., 2014. Green biosynthesis and characterization of zinc oxide nanoparticles using brown marine macroalga *Sargassum muticum* aqueous extract. Mater. Lett. 116, 275–277.

Baghour, M., 2019. Algal degradation of organic pollutants. In: Martínez, L., Kharissova, O., Kharisov, B. (Eds.), Handbook of Ecomaterials. Springer, Cham.

Bala, N., Saha, S., Chakraborty, M., Maiti, M., Das, S., Basu, R., Nandy, P., 2015. Green synthesis of zinc oxide nanoparticles using *Hibiscus subdariffa* leaf extract: effect of temperature on synthesis, anti-bacterial activity and anti-diabetic activity. RSC Adv. 5, 4993–5003.

Baldrian, P., 2003. Interactions of heavy metals with white-rot fungi. Enzym. Microb. Technol. 32, 78–91.

Bhattacharya, P., Swarnakar, S., Ghosh, S., Majumdar, S., Banerjee, S., 2019. Disinfection of drinking water via algae mediated green synthesized copper oxide nanoparticles and its toxicity evaluation. J. Environ. Chem. Eng. 7, 102867.

Borase, H.P., Patil, C.D., Suryawanshi, R.K., Koli, S.H., Mohite, B.V., Benelli, G., Patil, S.V., 2017. Mechanistic approach for fabrication of gold nanoparticles by *Nitzschia* diatom and their antibacterial activity. Bioprocess Biosyst. Eng. 40, 1437–1446.

Cabral, L., Giovanella, P., Gianello, C., Bento, F.M., Andreazza, R., Camargo, F.A.O., 2013. Isolation and characterization of bacteria from mercury contaminated sites in Rio Grande do Sul, Brazil, and assessment of methylmercury removal capability of a *Pseudomonas putida* V1 strain. Biodegradation 24, 319–331.

Cao, M., Wang, F., Zhu, J., Zhang, X., Qin, Y., Wang, L., 2017. Shape-controlled synthesis of flower-like ZnO microstructures and their enhanced photocatalytic properties. Mater. Lett. 192, 1–4.

Chandran, M., Yuvaraj, D., Christudhas, L., Ramesh, K.V., 2016. Bio synthesis of iron nanoparticles using the brown seaweed, *Dictyota dicotoma*. Biotechnol. Indian J. 12, 112.

Chapman, R.L., 2013. Algae: the world's most important "plants"—an introduction. Mitig. Adapt. Strateg. Glob. Change 18, 5–12.

Chelli, V.R., Golder, A.K., 2016. pH dependent size control, formation mechanism and antimicrobial functionality of bio-inspired AgNPs. RSC Adv. 6, 95483–95493.

Chetia, L., Kalita, D., Ahmed, G.A., 2017. Synthesis of Ag nanoparticles using diatom cells for ammonia sensing. Sens. Bio-Sens. Res. 16, 55–61.

Chokshi, K., Pancha, I., Ghosh, T., Paliwal, C., Maurya, R., Ghosh, A., Mishra, S., 2016. Green synthesis, characterization and antioxidant potential of silver nanoparticles biosynthesized from de-oiled biomass of thermotolerant oleaginous microalgae *Acutodesmus dimorphus*. RSC Adv. 6, 72269–72274.

Colin, J.A., Pech-Pech, I.E., Oviedo, M., Águila, S.A., Romo-Herrera, J.M., Contreras, O.E., 2018. Gold nanoparticles synthesis assisted by marine algae extract: biomolecules shells from a green chemistry approach. Chem. Phys. Lett. 708, 210–215.

Dahoumane, S.A., Yepremian, C., Djediat, C., Coute, A., Fievet, F., Coradin, T., Brayner, R., 2016. Improvement of kinetics, yield, and colloidal stability of biogenic gold nanoparticles using living cells of *Euglena gracilis* microalga. J. Nanopart. Res. 18, 79.

Deepak, P., Sowmiya, R., Ramkumar, R., Balasubramani, G., Aiswarya, D., Perumal, P., 2017. Structural characterization and evaluation of mosquito-larvicidal property of silver nanoparticles synthesized from the seaweed, *Turbinaria ornata* (Turner) J. Agardh 1848. Artif. Cells Nanomed. Biotechnol. 45, 990–998.

Deng, H., Ye, Z.H., Wong, M.H., 2004. Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China. Environ. Pollut. 132, 29–40.

Dobrucka, R., 2018. Synthesis of MgO nanoparticles using *Artemisia abrotanum* herba extract and their antioxidant and photocatalytic properties. Iran. J. Sci. Technol. Trans. A Sci. 42, 547–555.

Ebrahiminezhad, A., Bagheri, M., Taghizadeh, S.M., Berenjian, A., Ghasemi, Y., 2016. Biomimetic synthesis of silver nanoparticles using microalgal secretory carbohydrates as a novel anticancer and antimicrobial. Adv. Nat. Sci. Nanosci. Nanotechnol. 7, 015018.

El-Kassas, H.Y., Aly-Eldeen, M.A., Gharib, S.M., 2016. Green synthesis of iron oxide (Fe_3O_4) nanoparticles using two selected brown seaweeds: characterization and application for lead bioremediation. Acta Oceanol. Sin. 35, 89–98.

El-Khateeb, A.Y., Hamed, E., Ibrahim, F.Y., Hamed, S.E., 2019. Eco-friendly synthesis of selenium and zinc nanoparticles with biocompatible *Sargassum latifolium* algae extract in preservation of edible oils. J. Food Dairy Sci. 10, 141–146.

El-Rafie, H.M., El-Rafie, M., Zahran, M.K., 2013. Green synthesis of silver nanoparticles using polysaccharides extracted from marine macro algae. Carbohydr. Polym. 96, 403–410.

El-Seedi, H.R., El-Shabasy, R.M., Khalifa, S.A., Saeed, A., Shah, A., Shah, R., Iftikhar, F.J., Abdel-Daim, M.M., Omri, A., Hajrahand, N.H., Sabir, J.S.M., Zou, X., Halabi, M.F., Sarhan, W., Guo, W., 2019. Metal nanoparticles fabricated by green chemistry using natural extracts: biosynthesis, mechanisms, and applications. RSC Adv. 9, 24539–24559.

Eroglu, E., Chen, X., Bradshaw, M., Agarwal, V., Zou, J., Stewart, S.G., Duan, X., Lamb, R.N., Smith, S.M., Raston, C.L., Iyer, K.S., 2013. Biogenic production of palladium nanocrystals using microalgae and their immobilization on chitosan nanofibers for catalytic applications. RSC Adv. 3, 1009–1012.

Fatima, R., Priya, M., Indurthi, L., Radhakrishnan, V., Sudhakaran, R., 2020. Biosynthesis of silver nanoparticles using red algae *Portieria hornemannii* and its antibacterial activity against fish pathogens. Microb. Pathog. 138, 103780.

Feurtet-Mazel, A., Mornet, S., Charron, L., Mesmer-Dudons, N., Maury-Brachet, R., Baudrimont, M., 2016. Biosynthesis of gold nanoparticles by the living freshwater diatom *Eolimna minima*, a species developed in river biofilms. Environ. Sci. Pollut. Res. 23, 4334–4339.

Fu, L., Fu, Z., 2015. *Plectranthus amboinicus* leaf extract–assisted biosynthesis of ZnO nanoparticles and their photocatalytic activity. Ceram. Int. 41, 2492–2496.

Gallon, S.M.N., Alpaslan, E., Wang, M., Larese-Casanova, P., Londono, M.E., Atehortua, L., Pavon, J.J., Webster, T.J., 2019. Characterization and study of the antibacterial mechanisms of silver nanoparticles prepared with microalgal exopolysaccharides. Mater. Sci. Eng. C 99, 685–695.

Gardea-Torresdey, J.L., Parsons, J.G., Gomez, E., Peralta-Videa, J., Troiani, H.E., Santiago, P., Yacaman, M.J., 2002. Formation and growth of Au nanoparticles inside live alfalfa plants. Nano Lett. 2, 397–401.

Gardea-Torresdey, J.L., Gomez, E., Peralta-Videa, J.R., Parsons, J.G., Troiani, H., Jose-Yacaman, M., 2003. Alfalfa sprouts: a natural source for the synthesis of silver nanoparticles. Langmuir 19, 1357–1361.

Gonzalez-Ballesteros, N., Prado-Lopez, S., Rodriguez-Gonzalez, J.B., Lastra, M., Rodriguez-Arguelles, M.C., 2017. Green synthesis of gold nanoparticles using brown algae *Cystoseira baccata*: its activity in colon cancer cells. Colloids Surf. B 153, 190–198.

Govindaraju, K., Kiruthiga, V., Kumar, V.G., Singaravelu, G., 2009. Extracellular synthesis of silver nanoparticles by a marine alga, *Sargassum wightii* Grevilli and their antibacterial effects. J. Nanosci. Nanotechnol. 9, 5497–5501.

Govindaraju, K., Anand, K.V., Anbarasu, S., Theerthagiri, J., Revathy, S., Krupakar, P., Durai, G., Kannan, M., Subramanian, K.S., 2020. Seaweed (*Turbinaria ornata*)-assisted green synthesis of magnesium hydroxide [Mg (OH) 2] nanomaterials and their anti-mycobacterial activity. Mater. Chem. Phys. 239, 122007.

Gowdhami, B., Jaabir, M., Archunan, G., Suganthy, N., 2019. Anticancer potential of zinc oxide nanoparticles against cervical carcinoma cells synthesized via biogenic route using aqueous extract of *Gracilaria edulis*. Mater. Sci. Eng. C 103, 109840.

Griffiths, M., Harrison, S.T., Smit, M., Maharajh, D., 2016. Major commercial products from micro-and macroalgae. In: Algae Biotechnology. Springer, pp. 269–300.

Guo, Y., Jiang, N., Zhang, L., Yin, M., 2020. Green synthesis of gold nanoparticles from *Fritillaria cirrhosa* and its anti-diabetic activity on Streptozotocin induced rats. Arab. J. Chem. 13, 5096–5106.

Haverkamp, R.G., Marshall, A.T., 2009. The mechanism of metal nanoparticle formation in plants: limits on accumulation. J. Nanopart. Res. 11, 1453–1463.

Hussein, A.K., 2015. Applications of nanotechnology in renewable energies – a comprehensive overview and understanding. Renew. Sust. Energ. Rev. 42, 460–476.

Imani, S., Rezaei-Zarchi, S., Hashemi, M., Borna, H., Javid, A., Abarghouei, H.B., 2011. Hg, Cd and Pb heavy metal bioremediation by *Dunaliella* alga. J. Med. Plant Res. 5, 2775–2780.

Ishwarya, R., Vaseeharan, B., Subbaiah, S., Nazar, A.K., Govindarajan, M., Alharbi, N.S., Kadaikunnan, S., Khaled, J.M., Al-Anbr, M.N., 2018. *Sargassum wightii*-synthesized ZnO nanoparticles–from antibacterial and insecticidal activity to immunostimulatory effects on the green tiger shrimp *Penaeus semisulcatus*. J. Photochem. Photobiol. B: Biol. 183, 318–330.

Itroutwar, P.D., Govindaraju, K., Tamilselvan, S., Kannan, M., Raja, K., Subramanian, K.S., 2019. Seaweed-based biogenic ZnO nanoparticles for improving agro-morphological characteristics of rice (*Oryza sativa* L.). J. Plant Growth Regul. 39, 717–728.

Jain, K.K., 2007. Applications of nanobiotechnology in clinical diagnostics. Clin. Chem. 53, 2002–2009.

Jain, A., Wadhawan, S., Kumar, V., Mehta, S.K., 2018. Colorimetric sensing of Fe^{3+} ions in aqueous solution using magnesium oxide nanoparticles synthesized using green approach. Chem. Phys. Lett. 706, 53–61.

Jena, J., Pradhan, N., Nayak, R.R., Dash, B.P., Sukla, L.B., Panda, P.K., Mishra, B.K., 2014. Microalga *Scenedesmus* sp.: a potential low-cost green machine for silver nanoparticle synthesis. J. Microbiol. Biotechnol. 24, 522–533.

Jena, J., Pradhan, N., Dash, B.P., Panda, P.K., Mishra, B.K., 2015. Pigment mediated biogenic synthesis of silver nanoparticles using diatom *Amphora* sp. and its antimicrobial activity. J. Saudi Chem. Soc. 19, 661–666.

Kelly, D.J., Budd, K., Lefebvre, D.D., 2007. Biotransformation of mercury in pH-stat cultures of eukaryotic freshwater algae. Arch. Microbiol. 187, 45–53.

Khalafi, T., Buazar, F., Ghanemi, K., 2019. Phycosynthesis and enhanced photocatalytic activity of zinc oxide nanoparticles toward organosulfur pollutants. Sci. Rep. 9, 1–10.

Khaleelullah, M.M.S.I., Murugan, M., Radha, K.V., Thiyagarajan, D., Shimura, Y., Hayakawa, Y., 2017. Synthesis of super-paramagnetic iron oxide nanoparticles assisted by brown seaweed *Turbinaria decurrens* for removal of reactive navy blue dye. Mater. Res. Express 4, 105038.

Khalid, M., Khalid, N., Ahmed, I., Hanif, R., Ismail, M., Janjua, H.A., 2017. Comparative studies of three novel freshwater microalgae strains for synthesis of silver nanoparticles: insights of characterization, antibacterial, cytotoxicity and antiviral activities. J. Appl. Phycol. 29, 1851–1863.

Khalifa, K.S., Hamouda, R.A., Hanafy, D., Hamza, A., 2016. In vitro antitumor activity of silver nanoparticles biosynthesized by marine algae. Dig. J. Nanomater. Biostruct. 11, 213–221.

Khan, I., Saeed, K., Khan, I., 2019. Nanoparticles: properties, applications and toxicities. Arab. J. Chem. 12, 908–931.

Khanna, P., Kaur, A., Goyal, D., 2019. Algae-based metallic nanoparticles: synthesis, characterization and applications. J. Microbiol. Methods 163, 105656.

Khoshnamvand, M., Ashtiani, S., Liu, J., 2020. Acute toxicity of gold nanoparticles synthesized from macroalga *Saccharina japonica* towards *Daphnia magna*. Environ. Sci. Pollut. Res. 27, 22120–22126.

Klaus, T., Joerger, R., Olsson, E., Granqvist, C.G., 1999. Silver-based crystalline nanoparticles, microbially fabricated. Proc. Natl. Acad. Sci. 96, 13611–13614.

Koopi, H., Buazar, F., 2018. A novel one-pot biosynthesis of pure alpha aluminum oxide nanoparticles using the macroalgae *Sargassum ilicifolium*: a green marine approach. Ceram. Int. 44, 8940–8945.

Kumar, V., Yadav, S.K., 2009. Plant-mediated synthesis of silver and gold nanoparticles and their applications. J. Chem. Technol. Biotechnol. 84, 151–157.

Kumar, V.G., Gokavarapu, S.D., Rajeswari, A., Dhas, T.S., Karthick, V., Kapadia, Z., Shrestha, T., Barathy, I.A., Roy, A., Sinha, S., 2011. Facile green synthesis of gold nanoparticles using leaf extract of antidiabetic potent *Cassia auriculata*. Colloids Surf. B 87, 159–163.

Kumar, D.A., Palanichamy, V., Roopan, S.M., 2014. Green synthesis of silver nanoparticles using *Alternanthera dentata* leaf extract at room temperature and their antimicrobial activity. Spectrochim. Acta A Mol. Biomol. Spectrosc. 127, 168–171.

Kumaresan, M., Anand, K.V., Govindaraju, K., Tamilselvan, S., Kumar, V.G., 2018. Seaweed *Sargassum wightii* mediated preparation of zirconia (ZrO2) nanoparticles and their antibacterial activity against gram positive and gram negative bacteria. Microb. Pathog. 124, 311–315.

Leung, Y.H., Ng, A.M., Xu, X., Shen, Z., Gethings, L.A., Wong, M.T., Chan, C.M.N., Guo, M.Y., Ng, Y.H., Djurisic, A.B., Lee, P.K.H., Chan, W.K., Yu, L.H., Philips, D.L., Ma, A.P.Y., Leung, F.C.C., 2014. Mechanisms of antibacterial activity of MgO: non-ROS mediated toxicity of MgO nanoparticles towards *Escherichia coli*. Small 10, 1171–1183.

Liu, H., Zhang, H., Wang, J., Wei, J., 2020. Effect of temperature on the size of biosynthesized silver nanoparticle: deep insight into microscopic kinetics analysis. Arab. J. Chem. 13, 1011–1019.

Madeira, M.S., Cardoso, C., Lopes, P.A., Coelho, D., Afonso, C., Bandarra, N.M., Prates, J.A., 2017. Microalgae as feed ingredients for livestock production and meat quality: a review. Livest. Sci. 205, 111–121.

Madras, G., McCoy, B.J., 2003. Temperature effects during Ostwald ripening. J. Chem. Phys. 119, 1683–1693.

Mahdavi, M., Namvar, F., Ahmad, M.B., Mohamad, R., 2013. Green biosynthesis and characterization of magnetic iron oxide (Fe_3O_4) nanoparticles using seaweed (*Sargassum muticum*) aqueous extract. Molecules 18, 5954–5964.

Manam, D.V.K., Murugesan, S., 2014. Biological synthesis of silver nanoparticles from marine alga *Colpomenia sinuosa* and its in vitro anti-diabetic activity. Am. J. Bio-Pharmacol. Biochem. Life Sci. 3, 1–07.

Manikandakrishnan, M., Palanisamy, S., Vinosha, M., Kalanjiaraja, B., Mohandoss, S., Manikandan, R., Tabarasa, M., You, S., Prabhu, N.M., 2019. Facile green route synthesis of gold nanoparticles using *Caulerpa racemosa* for biomedical applications. J. Drug Deliv. Sci. Technol. 54, 101345.

Mata, T.M., Martins, A.A., Caetane, N.S., 2012. Microalgae processing for biodiesel production. In: Advances in Biodiesel Production, pp. 204–231.

McLachlan, J., 1985. Macroalgae (seaweeds): industrial resources and their utilization. In: Biosalinity in Action: Bioproduction with Saline Water, pp. 137–157.

Momeni, S., Nabipour, I., 2015. A simple green synthesis of palladium nanoparticles with *Sargassum* alga and their electrocatalytic activities towards hydrogen peroxide. Appl. Biochem. Biotechnol. 176, 1937–1949.

Moorthi, P.V., Balasubramanian, C., Mohan, S., 2015. An improved insecticidal activity of silver nanoparticle synthesized by using *Sargassum muticum*. Appl. Biochem. Biotechnol. 175, 135–140.

Mulbry, W., Kondrad, S., Pizarro, C., 2007. Biofertilizers from algal treatment of dairy and swine manure effluents: characterization of algal biomass as a slow release fertilizer. J. Veg. Sci. 12, 107–125.

Mulvaney, P., 1996. Surface plasmon spectroscopy of nanosized metal particles. Langmuir 12, 788–800.

Muthuchamy, N., Atchudan, R., Edison, T.N.J.I., Perumal, S., Lee, Y.R., 2018. High-performance glucose biosensor based on green synthesized zinc oxide nanoparticle embedded nitrogen-doped carbon sheet. J. Electroanal. Chem. 816, 195–204.

Muthukumar, T., Sambandam, B., Aravinthan, A., Sastry, T.P., Kim, J.H., 2016. Green synthesis of gold nanoparticles and their enhanced synergistic antitumor activity using HepG2 and MCF7 cells and its antibacterial effects. Process Biochem. 51, 384–391.

Nagarajan, S., Kuppusamy, K.A., 2013. Extracellular synthesis of zinc oxide nanoparticle using seaweeds of gulf of Mannar, India. J. Nanobiotechnol. 11, 39.

Narayanan, K.B., Sakthivel, N., 2010. Biological synthesis of metal nanoparticles by microbes. Adv. Colloid Interf. Sci. 156, 1–13.

Ojuederie, O.B., Babalola, O.O., 2017. Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. Int. J. Environ. Res. Public Health 14, 1504.

Ovais, M., Khalil, A.T., Ayaz, M., Ahmad, I., Nethi, S.K., Mukherjee, S., 2018a. Biosynthesis of metal nanoparticles via microbial enzymes: a mechanistic approach. Int. J. Mol. Sci. 19, 4100.

Ovais, M., Khalil, A.T., Islam, N.U., Ahmad, I., Ayaz, M., Saravanan, M., Shinwari, Z.K., Mukherjee, S., 2018b. Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. Appl. Microbiol. Biotechnol. 102, 6799–6814.

Ozturk, B.Y., Gursu, B.Y., Dag, I., 2020. Antibiofilm and antimicrobial activities of green synthesized silver nanoparticles using marine red algae *Gelidium corneum*. Process Biochem. 89, 208–219.

Palanisamy, S., Rajasekar, P., Vijayaprasath, G., Ravi, G., Manikandan, R., Prabhu, N.M., 2017. A green route to synthesis silver nanoparticles using Sargassum polycystum and its antioxidant and cytotoxic effects: an in vitro analysis. Mater. Lett. 189, 196–200.

Pan, H., Gao, H., Li, Q., Lin, Z., Feng, Q., Yu, C., Zhang, X., Dong, H., Chen, D., Cao, X., 2020. Engineered macroporous hydrogel scaffolds via pickering emulsions stabilized by MgO nanoparticles promote bone regeneration. J. Mater. Chem. B 8, 6100–6114.

Pandimurugan, R., Thambidurai, S., 2016. Novel seaweed capped ZnO nanoparticles for effective dye photodegradation and antibacterial activity. Adv. Powder Technol. 27, 1062–1072.
Papry, R.I., Ishii, K., Al Mamun, M.A., Miah, S., Naito, K., Mashio, A.S., Maki, T., Hasegawa, H., 2019. Arsenic biotransformation potential of six marine diatom species: effect of temperature and salinity. Sci. Rep. 9, 1–16.
Patel, V., Berthold, D., Puranik, P., Gantar, M., 2015. Screening of cyanobacteria and microalgae for their ability to synthesize silver nanoparticles with antibacterial activity. Biotechnol. Rep. 5, 112–119.
Patil, M.P., Kim, G.D., 2017. Eco-friendly approach for nanoparticles synthesis and mechanism behind antibacterial activity of silver and anticancer activity of gold nanoparticles. Appl. Microbiol. Biotechnol. 101, 79–92.
Patil, P.D., Gude, V.G., Mannarswamy, A., Deng, S., Cooke, P., Munson-McGee, S., Rhodes, I., Lammers, P., Nirmalakhandan, N., 2011. Optimization of direct conversion of wet algae to biodiesel under supercritical methanol conditions. Bioresour. Technol. 102, 118–122.
Patra, J.K., Baek, K.H., 2014. Green nanobiotechnology: factors affecting synthesis and characterization techniques. J. Nanomater. 2014. https://doi.org/10.1155/2014/417305.
Pereira, L., Mehboob, F., Stams, A.J., Mota, M.M., Rijnaarts, H.H., Alves, M.M., 2015. Metallic nanoparticles: microbial synthesis and unique properties for biotechnological applications, bioavailability and biotransformation. Crit. Rev. Biotechnol. 35, 114–128.
Petryayeva, E., Krull, U.J., 2011. Localized surface plasmon resonance: nanostructures, bioassays and biosensing—a review. Anal. Chim. Acta 706, 8–24.
Piccini, M., Raikova, S., Allen, M.J., Chuck, C.J., 2019. A synergistic use of microalgae and macroalgae for heavy metal bioremediation and bioenergy production through hydrothermal liquefaction. Sustain. Energy Fuel 3, 292–301.
Prasad, T.N., Kambala, V.S.R., Naidu, R., 2013. Phyconanotechnology: synthesis of silver nanoparticles using brown marine algae *Cystophora moniliformis* and their characterisation. J. Appl. Phycol. 25, 177–182.
Prasad, B.S., Padmesh, T.V.N., Kumar, V.G., Govindaraju, K., 2015. Seaweed (*Sargassum wightii* Greville) assisted green synthesis of palladium nanoparticles. Res. J. Pharm. Technol. 8, 392–394.
Priyadharshini, R.I., Prasannaraj, G., Geetha, N., Venkatachalam, P., 2014. Microwave-mediated extracellular synthesis of metallic silver and zinc oxide nanoparticles using macroalgae (*Gracilaria edulis*) extracts and its anticancer activity against human PC3 cell lines. Appl. Biochem. Biotechnol. 174, 2777–2790.
Pugazhendhi, A., Prabhu, R., Muruganantham, K., Shanmuganathan, R., Natarajan, S., 2019. Anticancer, antimicrobial and photocatalytic activities of green synthesized magnesium oxide nanoparticles (MgONPs) using aqueous extract of *Sargassum wightii*. J. Photochem. Photobiol. B: Biol. 190, 86–97.
Pytlik, N., Kaden, J., Finger, M., Naumann, J., Wanke, S., Machill, S., Brunner, E., 2017. Biological synthesis of gold nanoparticles by the diatom *Stephanopyxis turris* and in vivo SERS analyses. Algal Res. 28, 9–15.
Rai, M., Ingle, A., 2012. Role of nanotechnology in agriculture with special reference to management of insect pests. Appl. Microbiol. Biotechnol. 94, 287–293.
Rai, M., Ingle, A.P., Birla, S., Yadav, A., Santos, C.A.D., 2016. Strategic role of selected noble metal nanoparticles in medicine. Crit. Rev. Microbiol. 42, 696–719.
Rajathi, F.A.A., Parthiban, C., Kumar, V.G., Anantharaman, P., 2012. Biosynthesis of antibacterial gold nanoparticles using brown alga, *Stoechospermum marginatum* (kützing). Spectrochim. Acta A Mol. Biomol. Spectrosc. 99, 166–173.

Ramaswamy, S.V.P., Narendhran, S., Sivaraj, R., 2016. Potentiating effect of ecofriendly synthesis of copper oxide nanoparticles using brown alga: antimicrobial and anticancer activities. Bull. Mater. Sci. 39, 361–364.

Rao, M.D., Gautam, P., 2016. Synthesis and characterization of ZnO nanoflowers using *Chlamydomonas reinhardtii*: a green approach. Environ. Prog. Sustain. Energy 35, 1020–1026.

Ravichandran, A., Subramanian, P., Manoharan, V., Muthu, T., Periyannan, R., Thangapandi, M., Ponnuchamy, K., Pandi, B., Marimuthu, P.N., 2018. Phyto-mediated synthesis of silver nanoparticles using fucoidan isolated from *Spatoglossum asperum* and assessment of antibacterial activities. J. Photochem. Photobiol. B: Biol. 185, 117–125.

Salam, M.M.A., Kaipiainen, E., Mohsin, M., Villa, A., Kuittinen, S., Pulkkinen, P., Pelkonen, P., Mehtatalo, L., Pappinen, A., 2016. Effects of contaminated soil on the growth performance of young Salix (*Salix schwerinii* EL Wolf) and the potential for phytoremediation of heavy metals. J. Environ. Manag. 183, 467–477.

Salem, D.M., Ismail, M.M., Aly-Eldeen, M.A., 2019. Biogenic synthesis and antimicrobial potency of iron oxide (Fe_3O_4) nanoparticles using algae harvested from the Mediterranean Sea. Egypt. Egypt. J. Aquat. Res. 45, 197–204.

Senapati, S., Ahmad, A., Khan, M.I., Sastry, M., Kumar, R., 2005. Extracellular biosynthesis of bimetallic Au–Ag alloy nanoparticles. Small 1, 517–520.

Senapati, S., Syed, A., Moeez, S., Kumar, A., Ahmad, A., 2012. Intracellular synthesis of gold nanoparticles using alga *Tetraselmis kochinensis*. Mater. Lett. 79, 116–118.

Shah, M., Fawcett, D., Sharma, S., Tripathy, S.K., Poinern, G.E.J., 2015. Green synthesis of metallic nanoparticles via biological entities. Materials 8, 7278–7308.

Shakibaie, M., Forootanfar, H., Mollazadeh-Moghaddam, K., Bagherzadeh, Z., Nafissi-Varcheh, N., Shahverdi, A.R., Faramarzi, M.A., 2010. Green synthesis of gold nanoparticles by the marine microalga *Tetraselmis suecica*. Biotechnol. Appl. Biochem. 57, 71–75.

Shanab, S., Essa, A., Shalaby, E., 2012. Bioremoval capacity of three heavy metals by some microalgae species (Egyptian isolates). Plant Signal. Behav. 7, 392–399.

Sharma, M., Behl, K., Nigam, S., Joshi, M., 2018. TiO_2-GO nanocomposite for photocatalysis and environmental applications: a green synthesis approach. Vacuum 156, 434–439.

Sharma, A., Yu, H., Cho, I.S., Seo, H., Ahn, B., 2019. ZrO_2 nanoparticle embedded low silver lead free solder alloy for modern electronic devices. Electron. Mater. Lett. 15, 27–35.

Singaravelu, G., Arockiamary, J.S., Kumar, V.G., Govindaraju, K., 2007. A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. Colloids Surf. B 57, 97–101.

Singh, P., Kim, Y.J., Zhang, D., Yang, D.C., 2016. Biological synthesis of nanoparticles from plants and microorganisms. Trends Biotechnol. 34, 588–599.

Singh, P., Ahn, S., Kang, J.P., Veronika, S., Huo, Y., Singh, H., Chokkaligam, M., Farh, M.E., Aceituno, V.C., Kim, Y.J., Yang, D.C., 2018. In vitro anti-inflammatory activity of spherical silver nanoparticles and monodisperse hexagonal gold nanoparticles by fruit extract of *Prunus serrulata*: a green synthetic approach. Artif. Cells Nanomed. Biotechnol. 46, 2022–2032.

Singh, J., Kumar, S., Alok, A., Upadhyay, S.K., Rawat, M., Tsang, D.C., Bolan, N., Kim, K.H., 2019. The potential of green synthesized zinc oxide nanoparticles as nutrient source for plant growth. J. Clean. Prod. 214, 1061–1070.

Sivaraj, R., Rahman, P.K., Rajiv, P., Salam, H.A., Venckatesh, R., 2014. Biogenic copper oxide nanoparticles synthesis using *Tabernaemontana divaricate* leaf extract and its antibacterial activity against urinary tract pathogen. Spectrochim. Acta A Mol. Biomol. Spectrosc. 133, 178–181.

Souza, P.O., Ferreira, L.R., Pires, N.R., Filho, P.J.S., Duarte, F.A., Pereira, C.M., Mesko, M.F., 2012. Algae of economic importance that accumulate cadmium and lead: a review. Rev. Bras. Farmacogn. 22, 825–837.

Steinberg, R.A., 1936. Relation of accessory growth substances to heavy metals, including molybdenum, in the nutrition of *Aspergillus niger*. J. Agric. Res. 52, 439–448.

Subashchandrabose, S.R., Megharaj, M., Venkateswarlu, K., Naidu, R., 2015. Interaction effects of polycyclic aromatic hydrocarbons and heavy metals on a soil microalga, *Chlorococcum* sp. MM11. Environ. Sci. Pollut. Res. 22, 8876–8889.

Subramaniyam, V., Subashchandrabose, S.R., Thavamani, P., Megharaj, M., Chen, Z., Naidu, R., 2015. *Chlorococcum* sp. MM11—a novel phyco-nanofactory for the synthesis of iron nanoparticles. J. Appl. Phycol. 27, 1861–1869.

Suresh, J., Pradheesh, G., Alexramani, V., Sundrarajan, M., Hong, S.I., 2018a. Green synthesis and characterization of zinc oxide nanoparticle using insulin plant (*Costus pictus* D. Don) and investigation of its antimicrobial as well as anticancer activities. Adv. Nat. Sci. Nanosci. Nanotechnol. 9, 015008.

Suresh, J., Pradheesh, G., Alexramani, V., Sundrarajan, M., Hong, S.I., 2018b. Green synthesis and characterization of hexagonal shaped MgO nanoparticles using insulin plant (*Costus pictus* D. Don) leave extract and its antimicrobial as well as anticancer activity. Adv. Powder Technol. 29, 1685–1694.

Taghizadeh, S.M., Lal, N., Ebrahiminezhad, A., Moeini, F., Seifan, M., Ghasemi, Y., Berenjian, A., 2020. Green and economic fabrication of zinc oxide (ZnO) nanorods as a broadband UV blocker and antimicrobial agent. Nanomaterials 10 (3), 530.

Tolboom, S.N., Carrillo-Nieves, D., de Jesús Rostro-Alanis, M., de la Cruz Quiroz, R., Barceló, D., Iqbal, H.M., Parra-Saldivar, R., 2019. Algal-based removal strategies for hazardous contaminants from the environment – a review. Sci. Total Environ. 665, 358–366.

Tran, M., DePenning, R., Turner, M., Padalkar, S., 2016. Effect of citrate ratio and temperature on gold nanoparticle size and morphology. Mater. Res. Express 3, 105027.

Vanaja, M., Paulkumar, K., Baburaja, M., Rajeshkumar, S., Gnanajobitha, G., Malarkodi, C., Sivakavinesan, M., Annadurai, G., 2014. Degradation of methylene blue using biologically synthesized silver nanoparticles. Bioinorg. Chem. Appl. 2014. https://doi.org/10.1155/2014/742346.

Vasantharaj, S., Sathiyavimal, S., Senthilkumar, P., LewisOscar, F., Pugazhendhi, A., 2019. Biosynthesis of iron oxide nanoparticles using leaf extract of *Ruellia tuberosa*: antimicrobial properties and their applications in photocatalytic degradation. J. Photochem. Photobiol. B: Biol. 192, 74–82.

Venkatachalam, P., Priyanka, N., Manikandan, K., Ganeshbabu, I., Indiraarulselvi, P., Geetha, N., Muralikrishna, K., Bhattacharya, R.C., Tiwari, M., Sharma, N., Sahi, S.V., 2017. Enhanced plant growth promoting role of phycomolecules coated zinc oxide nanoparticles with P supplementation in cotton (*Gossypium hirsutum* L.). Plant Physiol. Biochem. 110, 118–127.

Venkatesan, J., Manivasagan, P., Kim, S.K., Kirthi, A.V., Marimuthu, S., Rahuman, A.A., 2014. Marine algae-mediated synthesis of gold nanoparticles using a novel *Ecklonia cava*. Bioprocess Biosyst. Eng. 37, 1591–1597.

Wang, C., Daimon, H., Onodera, T., Koda, T., Sun, S., 2008. A general approach to the size- and shape-controlled synthesis of platinum nanoparticles and their catalytic reduction of oxygen. Angew. Chem. 120, 3644–3647.

Wang, L., Min, M., Li, Y., Chen, P., Chen, Y., Liu, Y., Wang, Y., Ruan, R., 2010. Cultivation of green algae *Chlorella* sp. in different wastewaters from municipal wastewater treatment plant. Appl. Biochem. Biotechnol. 162, 1174–1186.

Xue, X., Penn, R.L., Leite, E.R., Huang, F., Lin, Z., 2014. Crystal growth by oriented attachment: kinetic models and control factors. CrystEngComm 16, 1419–1429.

Yazdani, A., Sayadi, M., Heidari, A., 2018. Green biosynthesis of palladium oxide nanoparticles using *Dictyota indica* seaweed and its application for adsorption. J. Water Environ. Nanotechnol. 3, 337–347.

Yigit, M.V., Moore, A., Medarova, Z., 2012. Magnetic nanoparticles for cancer diagnosis and therapy. Pharm. Res. 29, 1180–1188.

Yin, X., Chen, S., Wu, A., 2010. Green chemistry synthesis of gold nanoparticles using lactic acid as a reducing agent. Micro Nano Lett. 5, 270–273.

Yoon, J., Cao, X., Zhou, Q., Ma, L.Q., 2006. Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Sci. Total Environ. 368, 456–464.

Yugay, Y.A., Usoltseva, R.V., Silant'ev, V.E., Egorova, A.E., Karabtsov, A.A., Kumeiko, V.V., Ermakova, S.P., Bulgakov, V.P., Shkryl, Y.N., 2020. Synthesis of bioactive silver nanoparticles using alginate, fucoidan and laminaran from brown algae as a reducing and stabilizing agent. Carbohydr. Polym. 245, 116547.

Zhang, S., Qiu, C.B., Zhou, Y., Jin, Z.P., Yang, H., 2011. Bioaccumulation and degradation of pesticide fluroxypyr are associated with toxic tolerance in green alga *Chlamydomonas reinhardtii*. Ecotoxicology 20, 337–347.

Zhang, X., Li, W., Su, K., Zhang, R., Han, H., Deng, Y., Luo, S., 2019. Green synthesis of ZnO nano particles using *Chlorella vulgaris* extract as additives. In: IOP Conference Series: Materials Science and Engineering. 678, p. 012005.

Zhu, C., Zhang, S., Song, C., Zhang, Y., Ling, Q., Hoffmann, P.R., Li, J., Chen, T., Zheng, W., Huang, Z., 2017. Selenium nanoparticles decorated with *Ulva lactuca* polysaccharide potentially attenuate colitis by inhibiting NF-κB mediated hyper inflammation. J. Nanobiotechnol. 15, 1–15.