



Review article

Biogenic Synthesis and Applications of Nanoparticles Derived from Chlorophytic Marine Algae: A Comprehensive Review

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Keywords

Abstract

Nanoparticles Since last decade, researchers are trying for green synthesis of metallic Green nanoparticles using marine green algae. The marine resources are not completely synthesis explored for synthesis of metallic nanoparticles to overcome the challenges of Marine algae conventional methods. The renewable marine resources are available in ample Seaweeds along the Indian coastal areas and different coastal regions across the globe during Applications the course of the year. Researchers are concentrating on marine resources to synthesis of nanoparticles due to its high metal uptake capability, macro structure, more economic, nontoxic, ecofriendly and more reliable route for large scale production in future. Our present review draw the focus to reveal the current progresses in biogenic synthesis of stable metal and metallic oxide nanoparticles using green renewable marine resources. Furthermore, the architecture and applications such as antimicrobial, antibiofilm, synergistic and anticancer capabilities are briefly enumerated and uncover the future prospects of research in nanotechnology.

Introduction

It is very challenging to synthesize and handle the nano size particles when compared with its corresponding bulk material. Nanoparticles (NPs) are interesting scientific area of research as they fill the gap between nanomaterial and bulk materials (Comet et al., 2019; Amirjani et al., 2020). A bulk material has been found extremely different and interesting properties when transform into nano scale material. It has a tremendous potential to solve global issues due to its wide range of applications in drug delivery, diagnostics, imaging and biosensors (Yaqoob et al., 2020).

In recent years, researchers have been tried biological resources to synthesize nanoparticles which are substitute to physical and chemical methods. The traditional physical and chemical developed procedures are likely to use hazardous chemicals which are toxic and very destructive for human wellness and the surrounding environment (Varghese et al., 2015; Buchman et al., 2019). The properties of nanoparticles are entirely focused on the synthesis technique. The stabilizing and capping agents lead to toxic remainders adsorb on the surface of nanoparticles and restrict their applications (Cheon et al., 2019). Green synthesis is the best promising approach to exploit the natural resources to attain the objective of environment friendly protocol. Indeed, over the past decade, terrestrial organisms have been used for production of

metallic and metallic oxide nanoparticles. In current review article, we paying attention on various documented reports of green synthesis of metallic and metallic oxide nanoparticles and its applications by use of green macro algae (Shah et al., 2015).

Although considerable attention has been devoted to the biosynthesis of metallic nanoparticles using terrestrial plants and microbial systems, marine macroalgae (seaweeds) remain an underexplored biological resource despite their rich repertoire of bioactive metabolites and unique marine-derived biomolecules. To date, only a limited number of studies have reported the use of seaweeds for the green synthesis of metallic nanoparticles.

This review addresses this significant research gap by providing a comprehensive overview of the current progress in seaweed-mediated biosynthesis of metallic nanoparticles. It critically compiles and discusses the available literature on different marine algal species, the metallic nanoparticles synthesized, and their diverse biological and industrial applications. By highlighting the untapped potential of marine seaweeds as sustainable nanofactories, this review provides a valuable knowledge base and identifies future research directions for the development of novel, eco-friendly nanomaterials. The novelty of this review lies in its focused synthesis of the emerging field of

seaweed-mediated nanoparticle biosynthesis, which is expected to encourage researchers to further explore marine algae as promising resources for the green production of diverse metallic nanoparticles with applications in medicine, biotechnology, environmental remediation, agriculture, and other industrial sectors.

Seaweeds for synthesis of nanoparticles

The seaweeds can act as natural bio factories for producing particular nanoparticles. Out of total, 70% of earth surface is covered with sea water and having of huge variety of natural renewable marine resources which are not fully explored. Seaweeds have active phytochemical such as hydroxyl, carboxyl and amino functional groups, which are active metal-reducing, capping and stabilizing agents to synthesize controlled composition, shape and size of nanoparticles with unique physicochemical properties (Singh et al., 2020).

Exploring marine algae have been recently a thrust area of researchers because of its high tendency of metal intake and no loads of maintenance of culture for extracellular biogenic synthesis of NPs. Algae have broad diversity and habitat in the marine ecosystem. Approximately 841 marine algae taxa have been detected in inter-tidal deep-water areas in the Indian coastal regions (Veeragurunathan et al., 2022). It is further categorized as

microalgae and macro algae on the basis of morphological features. Microalgae are unicellular organisms, whereas macro algae are known as seaweed and multicellular with distinguished plant like body parts from centimeters to few meters in length. Macro algae grow in various form (tall or mats) and in several colours comprising Green (Chlorophyta), Red (Rhodophyta), Brown (Phaeophyta), Diatoms, Euglenoids, Cyanophyceae, Rhodophyceae etc (Jeffryes et al., 2015). For long periods, coastal populations used the sea weeds as a nutritional supplement and in medicinal remedies because it washed away to coastal lines due to heavy tides and wave strokes (Liu et al., 2012; Park et al., 2023). Recent studies revealed that seaweeds have bioactive compounds such as carotenoids, polysaccharides, proteins, vitamins and more secondary metabolites which are accountable for medicinal and anti-cancer properties (Nishinu et al., 1996; Khan et al., 2008; Ananthi et al., 2010; Namvar et al., 2012; Bibi et al., 2025).

However, the seaweeds phytoconstituents are act as capping agents and usually play a vital role by stop the further accumulation of nanoparticle to make it stable (Gautam and Van Veggel 2013). Moreover, research have revealed that uncovered nanoparticles are not stable because their atoms and molecules are attracted at their surface due to high surface energy, which speedily covering the external

surface and change surface properties. The existence of any harmful surface chemical will limit the therapeutic applications of nanoparticles (Ghaliaoui et al., 2024).

Nanoparticles have unique physiochemical properties which are entirely dissimilar from their bulk scale material (Bogunia Kubik and Sugisaka 2002; Goodsell 2004). Moreover, it is found that nanoparticles of the same composition can reveal the differences in behavior due to minor deviations in size, structure, surface reactivity, and surface jackets of nanoparticles (Thakkar et al., 2010; Gahlawat et al., 2025). The larger surface area to volume ratio of nanomaterial is a key factor accountable to influences the physiochemical properties (Slomberg et al., 2013). The particle morphology and dimensions are controlled during biosynthesis of nanoparticles and produced various shapes of nanoparticles (plates, sheets, tubes, wires etc.) which accounts for specific applications in biomedical, diagnostics, therapeutic treatments, electronics, water treatment and many more (Perez de Luque et al., 2012; Khot et al., 2012; Doria et al., 2012).

Classification of nanoparticles

NPs can be categorized on the basis of nature of material into organic, inorganic and carbon based. Inorganic NPs which are further classify into metallic, metallic oxide (magnetic nanoparticles and semiconductor) and metallic chalcogenides (detailed classification given in figure1) (Amer and Awwad 2021). Organic nanoparticles are made up of carbon and their biodegradable, non-toxic, drug transport efficiency and its stability are the novel features to make them supreme option in biomedical field for drug delivery (Tiwari et al., 2008). The nontoxic and efficient carrier features of the noble metallic nanoparticles accountable for its promising applications in biomedical including sensitive diagnostic assays, radiotherapy, and drug and gene delivery (Xie et al., 2010; Udayagiri et al., 2024). The metallic oxide nanoparticles are created by metal oxidise into metal oxide at room temperature to produce exceptional properties such as increased reactivity and efficiency than metal precursor (Tai et al., 2007). Recently, researchers focus on magnetic NPs due to its attractive properties and having potential to use in catalysis, magnetic resonance imaging, biomedical and environmental remediation (Lu et al., 2004; Gupta and Gupta 2005; Gleich and Weizenecker 2005).

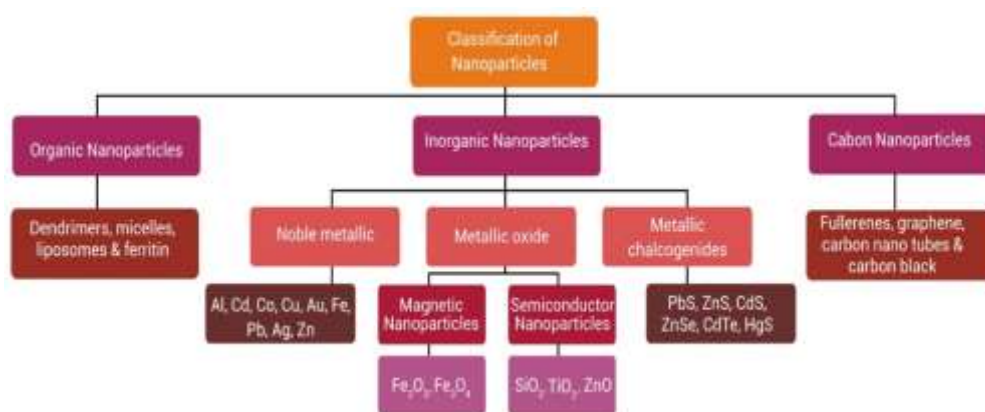


Fig. 1 Detailed Classification of nanoparticles based on nature of material

Nano scale materials can also be classified on the basis of shape and dimensions as given in figure 2.

Zero dimension nanoparticles: Nano scale lengths are measured in all three dimensions (length, breadth and height). Figure 2(a) depicts the nano dots, sphere and cluster like structures with high specific surface area add unique physiochemical properties in nanoparticles.

One dimension nanoparticles: Figure 2 (b) shows only one parameter length or breadth in the dimensional system such as nanowires, nanotubes and fibres etc. It strongly contributes

in technical applications like natural sensor, storing devices, and fibre-optic systems.

Two dimension nanoparticles: Figure 2 (c) represents only two parameters either length or breadth or height. It looks like a smooth surface sheet and having high adhesion property.

Three dimensional nanoparticles: Figure 2 (d) indicates all parameters of length, breadth and height. It is crystal like structure and having high carrier mobility make it strong contender in the field of nanotechnology (Singh and Singh 2017).

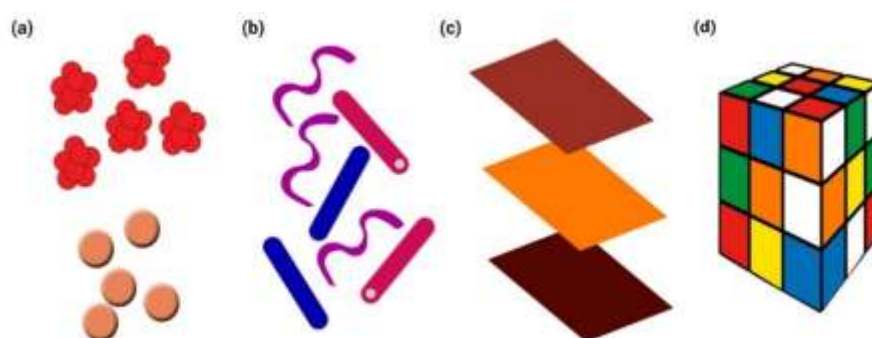


Fig. 2 Structural and dimensional Classification (a) Zero dimension clusters & spheres (b) One dimension nano fibers, nanowires/rods; (c) Two dimension structures; (d) Three dimension nanomaterial.

Synthesis of Nanoparticles Using Green Marine Algae

Several studies revealed that green synthesis of nanoparticles have been performed by preparing the water algal extract and molar metallic solution and followed by mixing a specific metallic salt solution with an aqueous algal extract of particular seaweed (Yu et al., 2019). The metallic ions have been reduced by bioactive compounds available in the seaweed

extract and change of colour of reaction mixture indicates the accumulation of nucleonic particles to form energetically stable nanoparticles of several shapes as detailed information in the figure 3. The formation of specific shape and symmetry of the nanoparticles depend on the salt solution, temperature, pH and time of the reaction mixture (Sicard et al., 2010; Thiurunavukkarau et al., 2022).

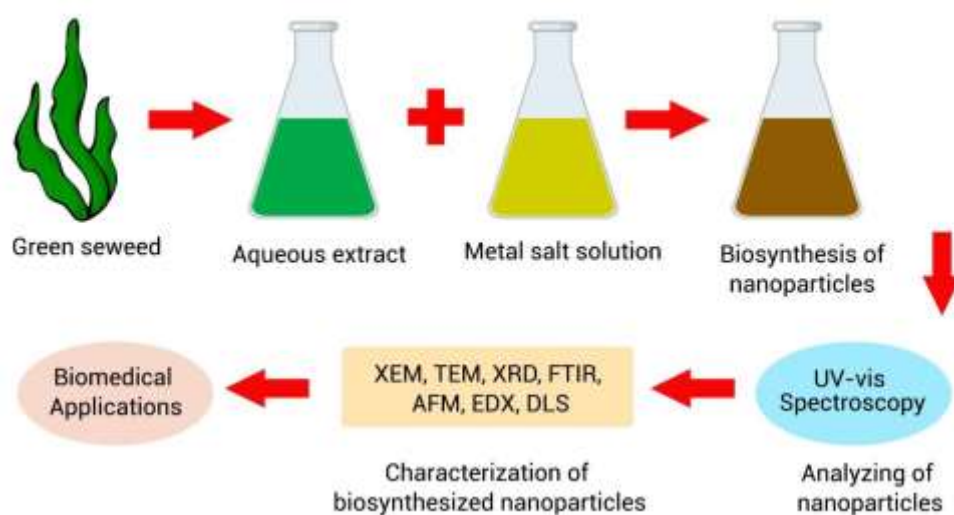


Figure 3. Schematic representation of biogenic synthesis and characterization of nanoparticles via green seaweeds.

However, an extensive investigation is desired to recognize and govern the influence of particular bioactive molecules in the algal water extract for biosynthesis protocol and the growth mechanisms of nanoparticle (Ai et al., 2011; Mittal et al., 2013). Presently, some researchers are still working on procedure parameters such as concentration of algal extract, concentration of metallic salt, pH of solution mixture, time period of reaction, and temperature using various green macro algae

repeatedly for biogenic synthesis of nanomaterial (Dahoumane et al., 2012; Dahoumane et al., 2014; Dahoumane et al., 2014). Meanwhile, these factors have a substantial influence on the superiority and properties of the manufactured nanoparticles (Parial et al., 2012).

Currently, researchers are paying attention to explore new techniques for biogenic synthesis of metal and metal oxide nanoparticles via marine green seaweeds (Romero Gonzalez et

al., 2003). The use of oceanic green algae to biosynthesize nanomaterial is a novel and emerging field of research. Various studies have shown that these bio-factories have the potential to create a metal and metal oxide nanoparticles at industrial level with wide range of applications using ecofriendly and nontoxic biogenic approaches (Asmathunisha and Kathiresan 2013; Patel et al., 2015).

Among the green seaweeds, species belonging to *Ulva* were the most extensively investigated for the biosynthesis of metallic nanoparticles, followed by *Enteromorpha*, *Caulerpa*, *Chaetomorpha*, *Cladophora*, *Codium*, and *Halimeda*. Silver nanoparticles (AgNPs) were the predominant nanoparticles synthesized, whereas only one study reported ZnO nanoparticles (*Ulva lactuca*), and no report on iron oxide nanoparticles was identified from the available data.

The synthesized nanoparticles exhibited considerable variation in size (2–256 nm) and morphology, with spherical nanoparticles being the most commonly reported, followed by hexagonal, cubical, triangular, sponge-like, irregular, and polycrystalline structures. Almost all studies demonstrated broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria, while several studies also reported antifungal activity.

Only one study (*Ulva fasciata*) investigated the synergistic effect of AgNPs with conventional antibiotics, indicating that this aspect remains largely unexplored. Similarly, antibiofilm activity was rarely evaluated despite its clinical importance. In contrast, anticancer activity was reported for nanoparticles synthesized from *Ulva lactuca*, *Ulva intestinalis*, *Enteromorpha compressa*, *Ulva fasciata*, and *Caulerpa scalpelliformis* against different cancer cell lines, suggesting their potential for biomedical applications.

A comparison of the published studies indicates that although almost all green seaweed-derived AgNPs exhibited antimicrobial activity, differences were observed in nanoparticle size, morphology, and biological efficacy among different seaweed species. These variations are likely associated with differences in phytochemical composition and synthesis conditions. Among all genera, *Ulva* species demonstrated the broadest range of biological activities, including antimicrobial, synergistic, ZnO nanoparticle synthesis, and anticancer applications, whereas studies on other genera mainly focused on antimicrobial evaluation (Sudhakar et al., 2023).

Now researchers need to pay attention to understand the comprehensive mechanisms to facilitate the reaction of biosynthesis of nanoparticles by using marine green algae and its various biomedical applications (Hussain et

al., 2005). In current time, a limited number of researchers have documented that the biosynthesis of silver, iron oxide and zinc oxide nanoparticles using several species of green seaweed with various size, shapes and showing antibacterial, antibiofilm, synergistic and anticancer properties as illustrated in table 1 (Azizi et al., 2017; Varmazyar et al., 2017; Sedaghat et al., 2019; Shanmuganathan et al., 2019; Suganya et al., 2019).

Metallic oxide nanoparticles

Till today, very few studies have been reported to use the different species of marine green algae for the biogenic synthesis of metal oxide nanoparticles. Metal oxides nanoparticles such as zinc oxide (ZnO) and ferric oxide (Fe₃O₄) are significant class of inorganic materials that have been widely explored due to their complex character than pure metal. Metal oxides have a vast array of distinct compositions, morphologies, architecture, and physiochemical properties (Malik et al., 2023).

The bonding of metal oxide in nature ranges from almost ionic to strongly covalent and even metallic. Researchers are paying their interest on metal oxide nanoparticles because of their distinctive and outstanding optical, electronic, and magnetic properties (Srivastava et al., 2013). Such specific physiochemical properties give huge industrial significance to metal oxide nanoparticles that include catalytic processes, electronics, sensors, magnetic

storage media, and conversion of solar energy (De Montferrand et al., 2013; Ramgir et al., 2013). Current literature portraying the biosynthesis of metal oxide nanoparticles through marine green algae is very restricted and based mainly on two metal oxide nanoparticles Iron oxide, zinc oxide and their applications.

Zinc oxide (ZnO) nanoparticles

Till now, very limited research on the biosynthesis of ZnO nanoparticles has been reported using green seaweed. It was recently reported that biosynthesis of zinc oxide nanoparticles using green algae extract *Ulva lactuca*. Nanoparticles range in size from 10-15 nm, and asymmetrical shaped like sponge. It was also reported that the ZnO nanomaterial showed exceptional bactericidal activity on Gram positive (*Bacillus licheniformis* and *Bacillus pumilis*) and Gram negative (*Escherichia coli* and *Proteus vulgaris*) bacteria. Similarly great potential for antibiofilm was also noted under both dark and sunlight conditions for *Ulva lactuca* seaweed. Using confocal laser scanning microscopy study on the effect of one single treatment with ZnO NPs on biofilm architecture of Gram-positive (*B. pumilus*, and *B. licheniformis*) and Gram negative (*E. coli*, and *P. vulgaris*) as given table 1 (Ishwarya et al., 2018).

Green Seaweeds	Biosynthesis of Silver, zinc oxide, Iron oxide nanoparticles			Antimicrobial activity	Synergistic effect	Antibiofilm activity	Anticancer activity	References
	Type of nano-particle	Size in nm	Shape					
<i>Ulva reticulata</i>	Ag	40-50	Spherical	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Bacillus sp.</i> , <i>Klebsiella pneumonia</i> , <i>Candida albicans</i> , <i>Candida parapsilosis</i> and <i>Aspergillus niger</i>				Dhanalakshmi et al., 2012; Devi and Bhimba 2014
<i>Ulva fasciata</i>	Ag	9-20	Spherical	<i>E. coli</i> , <i>Proteus mirabilis</i> , <i>Micrococcus leutus</i> , <i>Kocuria varians</i>	Ampicillin, gentamicin, ofloxacin and ciprofloxacin	-	Ehrlich Ascites Carcinoma (EAC)	Hamouda et al., 2018; Shahverdi et al., 2007; Fayaz et al., 2010
<i>Ulva rigida</i>	Ag	6.4	Spherical and hexagonal	<i>Aspergillus fumigatus</i>	-	-	Brine shrimp <i>Artemia salina</i>	Khalifa et al., 2014 El-Kassas et al., 2014
<i>Ulva lactuca</i>	Ag	20-56	Spherical	-	-	-	Breast cancer cell line MCF-7 Human colon cancer cell lines Caco-2 and HT-29	Devi and Bhimba 2012; Gonzalez Ballesteros et al., 2019
	ZnO	10-15	Asymmetrical shaped like sponge	Gram positive <i>Bacillus licheniformis</i> and <i>Bacillus pumilis</i> and Gram negative <i>Escherichia coli</i> and <i>Proteus vulgaris</i> bacteria	-	Gram positive <i>Bacillus pumilus</i> , and <i>Bacillus. Licheniformis</i> and Gram negative <i>E. coli</i> , and <i>Proteus. Vulgaris</i> bacteria	-	Ishwarya et al., 2018
<i>Ulva compressa</i>	Ag	0.315, 66.3	Sponge-like irregular structures	<i>Klebsiella pneumonia</i> , <i>Pseudomonas aeruginosa</i> , <i>E. coli</i> , <i>Enterococcus faecium</i> and <i>Staphylococcus aureus</i>				Minhas et al., 2018
<i>Cladophora glomerata</i>	Ag	0.150, 81.8	Sponge-like irregular structures	<i>Klebsiella pneumonia</i> , <i>Pseudomonas aeruginosa</i> , <i>E. coli</i> , <i>Enterococcus faecium</i> and <i>Staphylococcus aureus</i>				Minhas et al., 2018
<i>Ulva intestinalis</i>	Ag	14.2	Polycrystalline	-	-	-	Macrophage differentiated THP-1 (A) and NCI- H460 cells	Gonzalez Ballesteros et al., 2019
<i>Enteromorpha compressa</i>	Ag	4-24	Spherical	<i>E. coli</i> , <i>Klebsiella pneumoniae</i> , <i>Pseudomonas sp.</i> , <i>Staphylococcus aureus</i> and <i>Salmonella paratyphi</i> and fungal pathogens <i>Aspergillus flavus</i> , <i>A. niger</i> , <i>A. ochraceus</i> , <i>A. terreus</i> and <i>Fusarium moniliforme</i>	-	-	Ehrlich Ascites Carcinoma (EAC) cells	Ramkumar et al., 2017
<i>Enteromorpha intestinalis</i>	Ag	10-20	Spherical	<i>E. coli</i> , <i>Staphylococcus aureus</i> , <i>Vibrio cholera</i> , <i>Salmonella typhi</i> , <i>Candida albicans</i> , <i>C. tropicalis</i> and <i>C. krusei</i>	-	-	-	Raju et al., 2017

<i>Enteromorpha flexuosa</i>	Ag	2-32	Circular	<i>Bacillus subtilis</i> , <i>Bacillus pumilis</i> , <i>Enterococcus faecalis</i> , <i>Staphylococcus aureus</i> , <i>Staphylococcus epidermidis</i> , <i>E. coli</i> , <i>Klebsiella pneumonia</i> , <i>Pseudomonas aeruginosa</i> , <i>Aspergillus niger</i> , <i>Candida albicans</i> , <i>Saccharomyces cerevisiae</i>	-	-	-	Yousefzadi et al., 2014
<i>Cladophora fascicularis</i>	Ag	45		<i>Aeromonas hydrophila</i>	-	-	-	Rajasekar et al., 2019
<i>Caulerpa racemosa</i>	Ag	5-25	Almost spherical with few triangular Nanoparticles	<i>Staphylococcus aureus</i> and <i>Proteus mirabilis</i>	-	-	-	Kathiraven et al 2015; Edison et al., 2016
<i>Caulerpa scalpelliformis</i>	Ag	16.17 – 47.78		-	-	-	MCF-7 breast cancer cell line	Manikandan et al., 2019
<i>Caulerpa serrulata</i>	Ag	10 ± 2	Spherical	<i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i> , <i>Shigella sp.</i> , <i>Salmonella typhi</i> , and <i>E. coli</i>	-	-	-	Aboelfetoh et al., 2017
<i>Chaetomorpha antennina</i>	Ag	256.2 d.nm	Hexagonal and Cubical	<i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Enterococcus faecalis</i> , and <i>Proteus mirabilis</i>	-	-	-	Roy and Anantharaman 2017
<i>Chaetomorpha aerea</i>	Ag	14	Even shape and spherical nature	-	-	-	-	Sivakumar et al., 2018
<i>Chlorodesmis hildebrandtii</i>	Ag	10 -100		<i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Enterococcus faecalis</i> , and <i>Proteus mirabilis</i>	-	-	-	Roy and Anantharaman 2018
<i>Halimeda gracilis</i>	Ag	less than 100	Cubical, hexagonal and irregular shaped scatter and well distributed	<i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Enterococcus faecalis</i> , and <i>Proteus mirabilis</i>	-	-	-	Roy and Anantharaman 2018
<i>Codium tomentosum</i>	Ag	20 - 40	Irregular	<i>Bacillus subtilis</i> , <i>Klebsiella pneumoniae</i> and <i>Salmonella typhi</i>	-	-	-	Murugan et al., 2016
<i>Codium capitatum</i>	Ag	~30	Aggregated in clusters	-	-	-	-	Kannan et al., 2013

Table 1. Biosynthesis and bioactivities of silver, zinc oxide and iron oxide nanoparticles via green marine algae

Iron oxide (Fe₃O₄) nanoparticles

Current investigations have revealed that very less quantity of the literature is available for the biogenic synthesis of magnetic iron oxide nanoparticles using marine green seaweeds. It has found that iron oxide magnetic nanoparticles were synthesized by one step greener method which is simple, efficient and safe including reduction of ferric chloride solution using water extract of only brown seaweed (*Sargassum muticum*) (Mahdavi et al., 2013; Budlayan et al., 2021). The biocompatibility and magnetic properties of iron oxide nanoscale materials accountable for various therapeutic and drug delivery applications for treatment of tumors (Indira and Lakshmi 2010).

Bio prospectus of nanoparticles synthesized from seaweeds

Antibacterial activity

Now a day's emergence of multi drug resistance in pathogenic microorganisms is the major concern for the pharmaceutical industry to produce the potential drugs to treat the infected patients in the health care sector. Researchers are focusing on synthesis of nanoparticles using biological system at many places as an alternative of various pharmaceutical drugs. Marine algae considered as top bio factories in the competition of all biological materials such as plant, bacteria, fungi, sea grasses etc. because it's live and

dead dried biomass can be utilized for green synthesis of metallic nanoparticles (Davis et al., 2003). However, recent studies have shown that biomolecules of seaweed cell wall can act as biocatalysts in the reduction of metallic salts to synthesize the metal and metal oxide nanoparticles in a shorter period of time (Romero Gonzalez et al., 2003; Kumar et al., 2013; Mahdavi et al., 2013; Nagarajan et al., 2013), whereas other coating biomolecules of the natural extract control the creation of defined architecture of nano range particles and stop the aggregation of atoms and molecules which leads to particular size, symmetry, shape and surface reactivity of nanoparticles (Dhas et al., 2012; Khan et al., 2022).

Recent studies proposed the promising mechanism of action of nanoparticles on microbial cells, nanoparticles first adhere on the surface of microbial cell due to electrostatic attraction, vander Waals forces and receptors ligands and hydrophobic interactions (Armentano et al., 2014; Gao et al., 2014; Li et al., 2015; Luan et al., 2016). The positive charged nanoparticles interact with the negative charges cell surface of Gram positive and Gram negative bacteria. The Gram positive bacteria show more attraction towards nanoparticles due to high negative charge on the cell surface (Abbaszadegan et al., 2015). It is also revealed that Zeta potential of microbial cell surface drop down during interaction with nanoparticles which is also an important factor for adhesion

(Mohammed et al., 2017). The permeability of the membrane is changed due to disruption of membrane structure after adhesion of NPs which leads to the leakage of cellular components causing cell death (Hussain et al., 2005; Vasir and Labhasetwar 2008). Nanoparticles can influence the function of cell machinery by interacting with DNA, ribosomes, lysosomes and enzymes and reactive oxygen species (ROS) after penetrating in the cell (Yang et al., 2009; McQuillan and Shaw 2014; Xu et al., 2016;). Over the period of time, it has been suggested that nanoparticles show greater antimicrobial activity against Gram positive bacteria than Gram negative bacteria because Gram negative bacteria cell wall consist of lipopolysaccharide, lipoproteins and phospholipids which act as a barrier to penetrate the macromolecules (Sarwar et al., 2015). The antimicrobial activities of nanoparticles biosynthesized from various species of green macroalgae against different bacterial and fungal pathogens is given in detail in table 1.

6.2. Anticancer activity

In the present time, cancer is the very serious issue due to lack of proper drug delivery in the treatment of cancer. The studies revealed that nanoparticles of various size and shapes ranges from 1 to 100 nm have been developing for the wide applications in diagnostics and treatment of human cancers (Yezhelyev et al., 2006).

Now a days, scientists are emphasizing on drug delivery with green synthesized nanoparticles by use of different species of green algae against the different types of cancer cell lines *in vitro* condition and show the potential results against respective cancer cells as illustrated in table 1.

Synergistic effect

From another angle, the green marine algae show promising medicinal and pharmaceutical properties due to consist of bioactive phytochemicals. Biogenic synthesized silver (Ag) nanoparticles therefore have the potential to provide a remarkable synergistic activity against human Gram-positive and Gram-negative bacteria with enhanced medicinal properties for various antibiotics such as Ampicillin, gentamicin, ofloxacin and ciprofloxacin (Shaverdi et al., 2007; Fayaz et al., 2010) . It was found in the review that there is need to explore the biosynthesized silver, iron oxide and zinc oxide nanoparticles via green seaweeds for better results of synergistic effect.

Antibiofilm activity

Several studies have revealed that inorganic nano-sized particles (Ag and ZnO) are proficient agents of antimicrobial properties to inhibit the adhesion of bacterial cells and disrupt the biofilm matrix. Such nanoparticles follow various mechanisms, such as generation of reactive oxygen species (ROS), disruption of cell membrane integrity, synthesis of

biofilms or inhibition of enzymes (Applerot et al., 2012, Eshed et al., 2012; Prabhawathi et al., 2012). Currently, very less work has been done in the direction of antibiofilm activity of biogenic synthesized nanoparticles from ocean green algae (Ishwarya et al., 2018). It directs the researchers to develop the new techniques to synthesize nano scale metallic particles to show the potential antibiofilm effect.

Current studies have been focused on creating methods that biosynthesize magnetic nanoparticle with huge potential comprising controlled size, shape, symmetry and architecture of nanomaterial using green seaweeds (Wang et al., 2012). In common, nanoparticles surface coatings are considered a challenge in nano research due to accumulation behavior, instability in structure and cytotoxicity (Schweiger et al., 2011). In current review, we can found that biosynthesis of iron oxide nanoparticles from green seaweeds and its biomedical and pharmaceutical applications are totally unexplored in the field of nanotechnology.

Limitations and Challenges

The available studies are predominantly limited to the synthesis and preliminary characterization of silver nanoparticles, with very few reports on ZnO nanoparticles and no studies on iron oxide nanoparticles. Most investigations evaluated only antimicrobial

activity, while synergistic, antibiofilm, and mechanistic studies remain scarce. Furthermore, variations in synthesis protocols, characterization methods, nanoparticle concentrations, and biological assay conditions make direct comparison among studies difficult. In addition, in vivo studies, toxicity assessment, scale-up production, and clinical validation are still lacking, limiting the translation of green seaweed-mediated nanoparticles into practical biomedical and industrial applications.

Concluding remarks and future perspectives

Nanotechnology is an extremely encouraging area in biogenic synthesis of nanoparticles from vast freely available renewable bio-resources like green seaweeds. Researchers have shown the interest in these green bio resources due to their bioactive potential, stabilizing and capping agents to create the controlled size and architecture of metallic nanoparticles which is an inexpensive. Green seaweeds resources are yet to be explored for production at large scale, clean, nontoxic, stable and environmentally acceptable NPs and their commercial applications in biomedicine and health care sector in the upcoming future.

Till date, many queries are still unaddressed to understand the complete knowledge of mechanism and process behind the biosynthesis of stable nanoparticles. However, research is immediately needed to look forward

the unknown aspects in the field of greener synthesis of NPs.

- Ample work is desired to expand the competence of synthesis of nanoparticles using green seaweeds. The dimensions, architecture, and monodispersity are the three important factors of biological processes using seaweeds. The control on particle size, shape and monodispersity are necessary by fluctuating the synthesis parameters such as production conditions, substrate concentrations, reaction time, pH, and temperature to attain desired size and shape of nanoparticles.
- Extensive research is needed to know the comprehensive mechanisms facilitate the reaction of biosynthesis of nanoparticles and to explore the bioactive compounds of various seaweeds to develop simple, speedy, eco-friendly, and low cost technique to create the synthesis protocol commercially accessible should be considered.
- Several studies have revealed that the stability of algae assisted nanoparticles is a great challenge and to enhance the stability of the particles is the current focused area of research. Overall, nano biotechnologist that uses marine green algae mediated synthesis of nanomaterial and its applications in this area is still in its initial phase and has need of more research and development.

Conflict of interest

There is no conflict of interests regarding the publication of this paper.

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