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Review

Algal Nanoparticles and Their Antibacterial Activity: Current Research Status and Future Prospectives

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Abstract: Green nanotechnology is a promising technology that has a wide range of applications in pharmaceuticals today because they offer a higher surface-area-to-volume ratio. Algal-based nanoparticles (NPs) are the subject of intense research interest today for their potential to treat and prevent infections caused by infectious microorganisms that are antibiotic resistant. Algae contain a variety of therapeutically potential bioactive ingredients, including chlorophyll, phycobilin, phenolics, flavonoids, glucosides, tannins, and saponins. As a result, NPs made from algae could be used as therapeutic antimicrobials. Due to their higher surface-area-to-volume ratios compared to their macroscopic components, metallic nanoparticles are more reactive and have toxic effects on their therapy. For pharmaceutical and biomedical applications, green synthesis restricts the use of physical and chemical methods of metallic nanoparticle synthesis, and it can be carried out in an environmentally friendly and relatively low-cost manner. The majority of macroalgae and some microalgae have latent antimicrobial activity and are used in the synthesis of metallic nanoparticles. A potential application in the field of nanomedicine and the establishment of a potential pharmacophore against microorganisms may result from the synthesis of algal-based NPs. Only a few studies have been done on the potential antimicrobial, antifungal, and antibacterial activity of algae-based NPs. As a result, the study will concentrate on the environmentally friendly synthesis of various NPs and their therapeutic potential, with a focus on their antibacterial activity. Thus, the aim of this study is to review all the literature available on the synthesis and characterization of the algal nanoparticles and their potential application as an antibacterial agent.

Keywords: algae; antibacterial activity; cytotoxicity; nanoparticles

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1. Introduction

Nanotechnology is a rapidly growing and evolving area that includes engineering, science, and technology and operates on a nanoscale level. Nanoparticles, which are minute particles with dimensions that typically range from 1 to 100 nm, form the fundamental components of nanotechnology. Nanoparticles have numerous attractive qualities, including a high surface-to-volume ratio and relation with other particles, that make them useful in a variety of fields. Applications for nanoparticles are found in fields like electronics, cosmetics, biomedicine, and biotechnology. Because of their advantageous crystallographic and physiochemical properties, nanotechnology shows promise for further research and development. Nanoparticle synthesis can be accomplished through physical or chemical means, with some chemical methods utilizing harmful reducing agents [1–4]. These methods have several significant disadvantages, such as being vulnerable to contamination from precursor chemicals, utilizing harmful solvents, producing dangerous by-products, having a low rate of production, being expensive to produce, and consuming a lot of energy [4]. There is a requirement to substitute hazardous components with an ecologically sound approach for the creation of NPs. As a solution, scientists are directing their attention toward utilizing a biological process to create nanoparticles. This method is typically economical, non-hazardous, and environmentally friendly [5]. To date, various sources such as enzymes, plant extracts, bacteria, algae, and fungi have been employed in the production of nanoparticles [6–10] and have been used for the synthesis of NPs. It is surprising to note that in recent times, there has been a growing trend of creating nanoparticles through the use of algae.

Algae are a crucial group of photosynthetic organisms that hold both economic and environmental significance. They can be either single-celled or multicellular organisms that exist in various habitats, including marine water, freshwater, or on damp rocks [11–15]. Algae can be grouped into two groups, macroalgae and microalgae. They are extensively employed in a range of fields, including agriculture, pharmaceuticals, medicine, cosmetics, and aquaculture [16–22]. Furthermore, algae are a valuable resource for numerous commercial products, like biofuels and natural dyes [23,24]. Thus far, in the creation of metallic nanoparticles, various types of algae have been utilized, including Chlorophyceae, Phaeophyceae, Cyanophyceae, Rhodophyceae, Diatoms, and Euglenoids [25]. Algae are considered to be an excellent choice for the biosynthesis of nanoparticles due to their capacity to gather and minimize metal ions. Furthermore, algae provide several advantages such as ease of manipulation, production at lower temperatures with enhanced energy efficiency, reduced toxicity, and decreased environmental risk [26].

2. Algal Nanoparticles vs. Chemically Synthesized Nanoparticles

Algal nanoparticles, derived from several micro and macroalgae, offer several advantages over chemical nanoparticles [27]. Here are some of the key advantages:

(i) Renewable and Sustainable: Algae are photosynthetic organisms that can be sustainably cultivated using sunlight, water, and carbon dioxide. This makes algal nanoparticles a renewable and eco-friendly alternative to chemical nanoparticles, which often require energy-intensive manufacturing processes and non-renewable resources [28].

(ii) Biocompatibility: Algal nanoparticles are typically composed of organic materials that are biocompatible and non-toxic. They have a reduced likelihood of causing adverse effects when interacting with biological systems, making them suitable for various biomedical applications [28,29].

(iii) Natural Products: Algae produce a wide range of bioactive compounds, such as pigments, polysaccharides, and proteins. By utilizing algal nanoparticles, these natural products can be incorporated into the nanoparticle formulation, thereby enhancing their functionality and potential applications [28,29].

(iv) Cost-effectiveness: Algae can be cultivated using simple and cost-effective methods, such as open pond systems or photobioreactors. The relatively low-cost production process of algal nanoparticles can make them economically viable compared to chemically synthesized nanoparticles [28–30].

(v) Versatility: Algal nanoparticles can be engineered to have a variety of sizes, shapes, and surface functionalities. This versatility allows for tailoring their properties to specific applications, including drug delivery, bioimaging, water treatment, and environmental remediation [30–32].

(vi) Reduced Environmental Impact: The production of chemical nanoparticles often involves the use of toxic solvents, hazardous materials, and energy-intensive processes, which can have a negative impact on the environment. Algal nanoparticles, on the other hand, can be produced using greener and more sustainable methods, minimizing their environmental footprint [30–32].

(vi) Scalability: Algae can be grown in large-scale bioreactors, enabling the production of algal nanoparticles in significant quantities. This scalability is crucial for applications that require large volumes of nanoparticles, such as industrial processes and commercial products [30–32].

It is worth noting that the field of algal nanoparticles is still developing, and their advantages and limitations continue to be explored. Due to their usage of both living and dried biomass in the production of metallic NPs, algae are frequently referred to as "Bio-nanofactories" [33]. Various algae species, including *Spirulina platensis*, *Lyngbya majuscule*, *Chlorella vulgaris*, and *Ulva fasciata* have been utilized in a cost-effective manner for the generation of silver NPs [34–36]. Algae are just as important as other microorganisms like yeast, bacteria, and fungi when it comes to producing nanoparticles. As a result, investigating the use of algae in the biosynthesis of nanomaterials has led to the development of a novel branch called phyco-nanotechnology [37]. Therefore, this review is focused on the capabilities of algae-mediated biosynthesis of nanoparticles, the mechanisms that are involved in the process, their importance in biomedical applications with a special emphasis on their antibacterial properties, and the possibilities that lie ahead in this field.

3. Algae as a Host for Nanoparticles Production

As mentioned earlier, algae contain large amounts of complex molecules and have the ability to absorb high levels of heavy metal ions and transform them into more flexible forms using bio reduction. Extracts from algae usually contain various substances like pigments, minerals, proteins, polyunsaturated fatty acids, and carbohydrates [31]. In addition, the synthesis of nanoparticles through algae is faster than that of other biological synthesis processes [38]. Because of these characteristics, both living and dead algae are utilized as model organisms for the environmentally friendly synthesis of bionanomaterials. In this process, the formation of nanoparticles is identified using UV-visible absorption spectroscopy, SEM, and TEM, while the functional groups responsible for the bioreduction are analyzed through FTIR [39].

In the realm of nanotechnology, different varieties of algae, starting from Chlorophyceae and followed by Phaeophyceae, Cyanophyceae, and Rhodophyceae, as well as others like euglenoids and diatoms, have been discovered to produce diverse forms of metallic NPs such as palladium, gold, iron, and silver [25] (Figure 1).

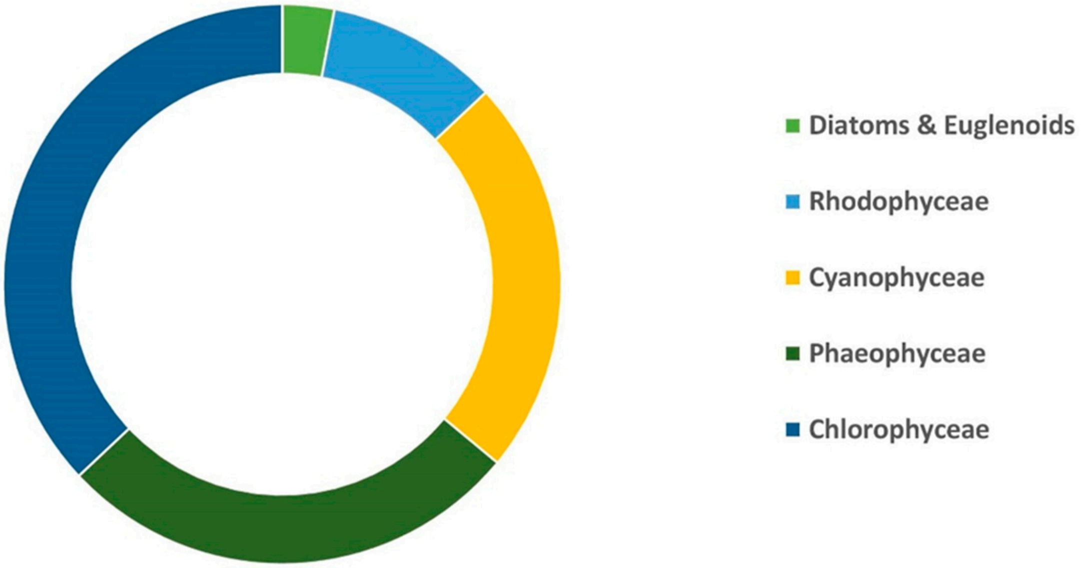

Figure 1. Involvement of different categories of algae in the production of metallic nanoparticles in recent years.

4. Mechanism Involved in Phyco-Synthesis of Nanoparticles

Algae have a noticeable capacity to accumulate ions of heavy metal and transform them into more flexible forms. This quality has made them attractive candidates for creating a variety of nanomaterials, particularly metallic nanoparticles. As a result, algae are considered as model organisms for the production of these nano-materials [40].

To create nanoparticles (NPs) using algae, a solution containing metal ions is mixed with an extract from the algae. Biochemical compounds present in algae have the ability to reduce the charge of metal ions to a state of zero valences. This bio-reduction process consists of three stages. In the activation phase, metal ions are reduced and nucleation occurs, which is visible from the color change of the solution. During the growth phase, the nucleated metal elements combine to form nanoparticles of different sizes and shapes. The ultimate shape of the nanoparticles is determined in the final termination phase. Several factors, viz. time, pH, substrate concentration, and temperature, influence the physical properties of the nanoparticles [41].

The production of nanoparticles (NPs) from algae can occur either inside the cell or outside. The intracellular method involves the biosynthesis of NPs within the algae cell, as illustrated in Figure 2. NADPH or NADPH-dependent reductase is released during metabolic processes, and it functions as a reducing agent [25,42]. As an example, intracellular biosynthesis of AuNPs was achieved by incubating chloroauric acid with *Ulva intestinalis* and *Rhizoclonium fontinale* for 72 h at 20 °C. The biosynthesis was illustrated by an observable color alteration of the thallus from green to purple. In another experiment, *Klebsormidium flaccidum* in a silica gel suspension also showed a similar color change, indicating the cells' ability to reduce the gold precursor. The existence of reduced gold precursor salt in the thylakoid membrane was confirmed through TEM analysis, which revealed the presence of dark-colored spots [43]. Senapati and co-workers (2012) provided evidence of a comparable intracellular production of AuNPs in *Tetraselmis kochinensis* by way of the cell wall of algae [44].

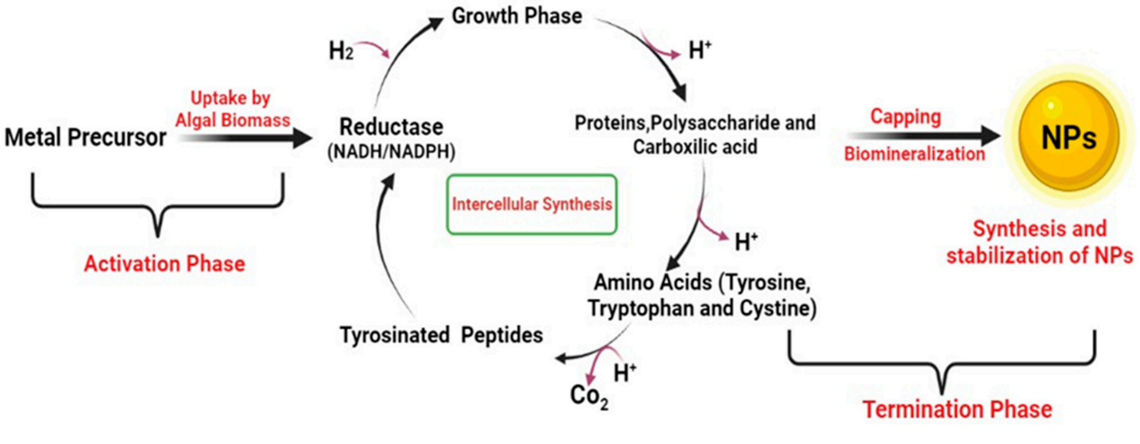

Figure 2. Intracellular synthesis methods of algal nanoparticles.

The extracellular method of nanoparticle generation comprehends the attachment of metal ions to the exterior of algal cells, where metabolites subsequently reduce them [45]. Although the extracellular approach is ideal for purification purposes, particular pre-treatments like blending and washing of algal biomass are necessary, as depicted in Figure 3 [46]. The shape, agglomeration, and size of nanoparticles are influenced by various physiochemical conditions like temperature and pH [42,47–49]. The production of AuNPs utilizing the extracellular method by *S. platensis* was confirmed by a surface plasmon climax at 530 nm, indicating the involvement of various biomolecules in the algae-assisted production of NPs [50].

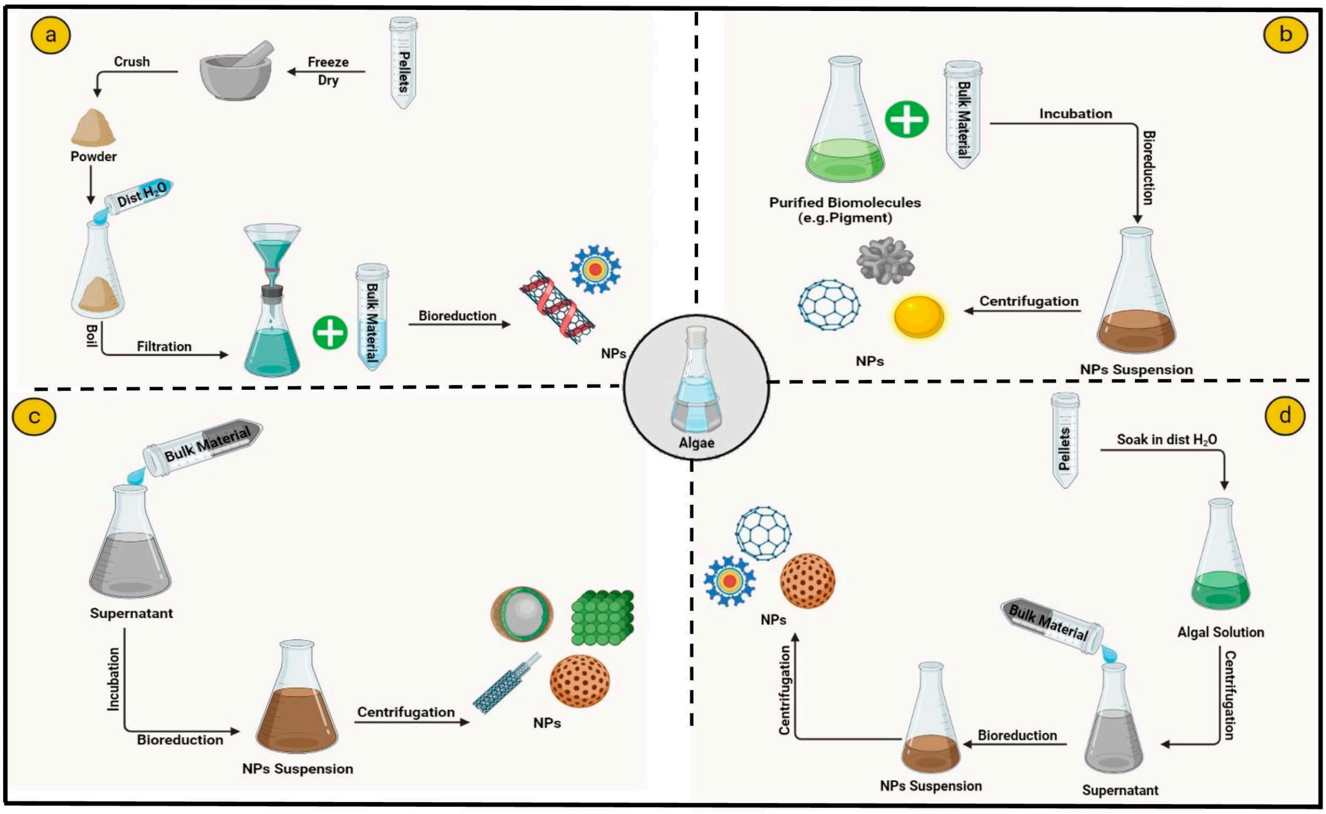

Figure 3. Different extracellular synthesis methods of algal nanoparticles: (**a**) cell biomass mediated, (**b**) biomolecules mediated, (**c**) cell-free media mediated, (**d**) cell filtrate mediated.

5. Different Classes of Algae Involved in the Synthesis of Nanoparticles

Algae are a varied collection of unicellular/multicellular, aquatic, and photoautotrophic organisms that have been categorized into various classes, including blue-green algae, green algae, red algae, and brown algae [51,52]. Algae are a preferred option for the biofabrication of diverse metallic and metal oxide nanoparticles due to their rapid growth rate, ease of manipulation, and biomass expansion rate, which is generally ten times quicker than higher plants. Several algal strains have been studied for the eco-friendly production of various types of nanoparticles, as described below.

5.1. Brown Algae-Mediated Biosynthesis of NPs

Due to their high sterol content, brown algae are classified as members of the Fucales order. In the process of creating NPs, these sterols act as capping and reducing agents [53]. As listed in Table 1, numerous kinds of brown algal species have been effectively used to create metal oxide (zinc oxide and titanium oxide) and metallic (silver and gold) NPs. Due to their remarkable physicochemical characteristics in comparison to their bulk forms, AgNPs are among the most often generated metallic NPs from various algae strains [54,55]. It has been observed that a variety of brown algae species, including *Turbinaria conoides*, *Gelidiella acerosa*, *Cystophora moniliformis*, *Desmarestia menziesii*, *Padina pavonica*, and *Sargassum polycystum*, are useful for the production of AgNPs [36,56–59].

According to a source, AgNPs with a round shape and a size of 96 nm were produced through an extracellular method using *T. conoides*. These AgNPs displayed excellent antibacterial properties against several pathogenic bacteria. The report also mentioned that organic molecules present in *Turbinaria* species have been identified as the reducing agents in synthesizing AgNPs [54,58,60]. Gold nanoparticles (AuNPs) have also been generated from different strains of brown algae, which possess various biologically active properties such as anti-bacterial, anti-coagulant, and anti-fouling activities [61]. Several species, including *Sargassum myriocystum*, *Cystoseira baccata*, *Sargassum wightii*, *Ecklonia cava*, *Fucus* *vesiculosus*, *Stereospermum marginatum*, *Dictyota bartayresianna*, and *Padina gymnospora*, have been recorded for the green synthesis of AuNPs [62], as described in Table 1. Brown algae have been found to be capable of synthesizing not only metallic nanoparticles but also metal oxide NPs, including titanium oxide nanoparticles (TiO_2 NPs) and zinc oxide nanoparticles (ZnO NPs) [63,64].

5.2. Red Algae-Mediated Biosynthesis of NPs

Red algae, which are classified under the Rhodophyta family, are mainly utilized as a food source in various countries because of their distinct taste and high content of significant proteins and vitamins [65]. These vitamins and proteins appear to be ideal for minimizing and stabilizing the production of nanoparticles through the use of algae. Nonetheless, the production of nanoparticles from red algae found in seaweed is still in the early stages of development because of obstacles such as self-aggregation, sluggish growth of crystallization, and issues with stability [66]. *Porphyra vietnamensis* is a well-known type of red algae that has been thoroughly investigated for its capacity to generate various types of nanoparticles, thanks to the existence of a potential reducing agent like sulfated polysaccharides [67]. There are several other red algae strains documented in literature for the synthesis of silver NPs, including *Kappaphycus* sp., *Gracilaria dura*, *Kappaphycus alvarezii*, *Palmaria decipiens*, *Gelidiella acerosa*, and several others, as listed in Table 1.

In contrast to the extensive research on the biosynthesis of silver nanoparticles, there have been relatively few investigations into the utilization of red algae for creating gold nanoparticles. One type of marine red algae, *Lemanea fluviatilis*, has been studied as a potential candidate for producing gold nanoparticles by utilizing chloroauric acid as the precursor salt [24,68]. Moreover, other species such as *Corallina officinalis, Chondrus crispus, Galaxaura elongata,* and *Kappaphycus alvarezii* have also been shown to facilitate the biosynthesis of gold NPs [39,69]. Apart from generating individual metallic nanoparticles, *Gracilaria edulis*, a type of red algae, has been proven to be proficient in creating bimetallic Ag–Au nanoparticles by utilizing different molar ratios of $HAuCl_4$ and $AgNO_3$. The bimetallic nanoparticles synthesized by this method have demonstrated potent anti-cancer properties against human breast cancer cells [70].

5.3. Blue-Green Algae-Mediated Biosynthesis of NPs

Blue-green algae (BGA), which are categorized under the order of Chroococcales, occupy an unusual position in the biological realm and are considered to be analogous to single-celled bacteria. BGA has been widely employed in the creation of various kinds of nanoparticles, unlike brown and red algae, as stated in Table 1. *Spirulina platensis* is the main source of AgNPs produced by blue-green algae. However, various other blue-green algae species, such as *Oscillatoria willei*, *Plectonema boryanum*, *Microchaete diplosiphon*, and *Cylindrospermum stagnale*, have also synthesized AgNPs of various shapes and sizes [59,71].

Research has shown that *S. platensis* is also involved in the biosynthesis of AuNPs. Numerous studies have documented the extracellular creation of spherical, octahedral, and cubic AuNPs using *S. platensis*, demonstrating the role of proteins and peptides as reducing agents. Another notable BGA, *Phormidium valderianum*, has also produced intracellular mono-dispersive triangular AuNPs [72].

Aside from generating individual metallic nanoparticles, *S. platensis* has been observed to take part in the biosynthesis of bimetallic nanoparticles. Meanwhile, *Chlamydomonas reinhardtii* has been discovered to facilitate the creation of cadmium sulfide bimetallic nanoparticles (CdSNPs), which have various applications in areas like biosensors, LEDs, and photo-catalysis [73].

5.4. Green Algae-Mediated Biosynthesis of NPs

Micro and macro green algae are the two principal divisions of green algae based on the environment in which they live. Unlike macro green algae, which are multicellular and mostly occupy marine ecosystems, micro green algae are single-celled and are found in freshwater environments. Currently, they are widely used to produce a range of metal oxide NPs, monometallic and bimetallic, from green algae [74].

Over 20 various species of micro green algae have been employed thus far in the biosynthesis of AgNPs. Almost all of these species produce extracellular AgNPs of varying sizes and shapes, including *Pithophora oedogonia*, *Chlorococcum humicola*, *Chlorella vulgaris*, *C. reinhardtii*, and *Enteromorpha flexuosa* [75,76]. Additionally, there has been a great deal of recent research on the biosynthesis of AuNPs mediated by green microalgae, as described in Table 1. *Pithophora crispa*, which thrives at higher altitudes, is one of the most commonly exploited species of micro green algae for the synthesis of AuNPs. In addition to AuNPs and AgNPs, micro green algae have been utilized in the creation of semiconductor nanoparticles, including silicon nanoparticles that are employed as bio-indicators in various industrial waste products [77].

Green macroalgae, which are also referred to as bio-factories, have the ability to generate metallic nanoparticles thanks to the presence of several valuable compounds that facilitate nanoparticle reduction and capping [78]. In recent times, multiple strains of green macroalgae have been utterly employed in the production of metallic nanoparticles, as outlined in Table 1. *Ulva fasciata* is among the most beneficial species of green macroalgae and was employed in creating nano-sized silver colloids. These colloids were then adapted to cotton fabric to evaluate their antimicrobial properties [79]. In another study, *Gracilaria edulis* was used to synthesize spherical AgNPs and octahedral ZnONPs. Green macroalgae strains like *Rhizoclonium fontinale* and *Prasiola crispa* have also been successful in generating AgNPs, in addition to AuNPs [80].

Table 1. Biosynthesis of NPs by using algae.

Class	Algal Strain	Type of NPs	Site of Synthesis	Shape and Size	References
Pheophyceae	*Turbinaria conoides*	Ag	Extracellular	Spherical, 96 nm	[58]
	Gilidiella acerosa	Ag	Extracellular	Spherical, 18–46 nm	[81]
	Padina tetrastromatica1	Ag	Extracellular	Spherical, 4 nm	[82]
	Sargassum muticum	Au	Extracellular	Anisotropic and poly-dispersed, 4–45 nm	[83]
	Cystoseira baccata	Au	Extracellular	Poly-crystalline and spherical, 8.4 ± 2.2 nm	[84]
	Sargassum muticum	ZnO	Extracellular	Hexagonal, 30–57 nm	[85]
Rhodophyceae	*Gracilaria edulis*	Ag	Extracellular	Spherical, 12.5–100 nm	[86]
	Gracilaria birdiae	Ag	Extracellular	Spherical, 20.3 nm	[87]
	Galaxaura elongate	Au	Extracellular	Rod, truncated and triangular shaped, 3.85–77.13 nm	[88]
	Chondrus crispus	Au	Extracellular	Spherical and polyhedral, 30–50 nm	[39]
	Corallina officinalis	Au	Extracellular	-	[89]
Cyanophyceae	*Spirulina platenesis*	Au	Extracellular	Monodispersed and spherical, 2–8 nm	[90]
	Nostoc ellipsosporum	Au	Extracellular	Decahedral and icosahedron, 20–40 nm	[91]
	Microchaete	Ag	Extracellular	Polydispersed and spherical, 80 nm	[92]
	Cylindrospermum stagnale	Ag	Extracellular	Pentagonal, 38–88 nm	[71]
	Chlamydomonas reinhardtii	CdSNPs	Extracellular	-	[73]
	Oscillato riawillei	Ag	Extracellular	Spherical, 10–25 nm	[93]

Table 1. *Cont.*

Class	Algal Strain	Type of NPs	Site of Synthesis	Shape and Size	References
Chlorophyceae	*Scencedesmus* sp.	Ag	Extracellular	15–20 nm	[94]
	Pithophora oedogonia	Ag	Extracellular	Cubical and hexagonal, 24–55 nm	[24]
	Plectonema boryanum	Ag	Intracellular	Less than 10 nm	[31]
	Chlorococcum humicola	Ag	Intracellular	Spherical, 16 nm	[76]
	Klebsormidium flaccidum	Au	Intracellular	10–20 nm	[43]
	Spirogyra varians	Ag	Extracellular	17.6 nm	[95]
	Ulva reticula	Ag	Extracellular	Spherical, 40–50 nm	[96]
	Cholera vulgaris	Si	Extracellular	Spherical	[97]

6. Applications of Phyco Nanoparticles

Nanoparticles created through green methods are basically biocompatible and lack toxic chemicals on their surfaces since they do not employ reducing agents or external capping. Algae-mediated nanoparticles are especially appealing for biomedical purposes since they do not necessitate the employment of harmful substances for stabilization and reduction [98]. This is because algae naturally contain biomolecules that are non-toxic, making them a preferred option for various biomedical applications [99,100]. Therefore, this section goes on to provide more information on the antibacterial properties of algae-mediated NPs.

In Vito Antibacterial Activity

The overuse of antibiotics for treating bacterial infections has resulted in the emergence of bacterial strains that are resistant to multiple drugs. This presents a significant health challenge worldwide as there is a need for effective and safe treatment options for these drug-resistant strains. There has been a trend towards using nanoparticles (NPs) as a substitute for antibacterial agents, which have been demonstrated to be incredibly effective in eradicating bacteria. NPs can eliminate bacteria by interfering with the cell membrane and creating reactive oxygen species (ROS), providing them with a wide spectrum of antibacterial activity against both gram (+ve) and gram (−ve) bacteria [101]. The mechanism of action of algal nanoparticles on bacterial cells is illustrated in Figure 4.

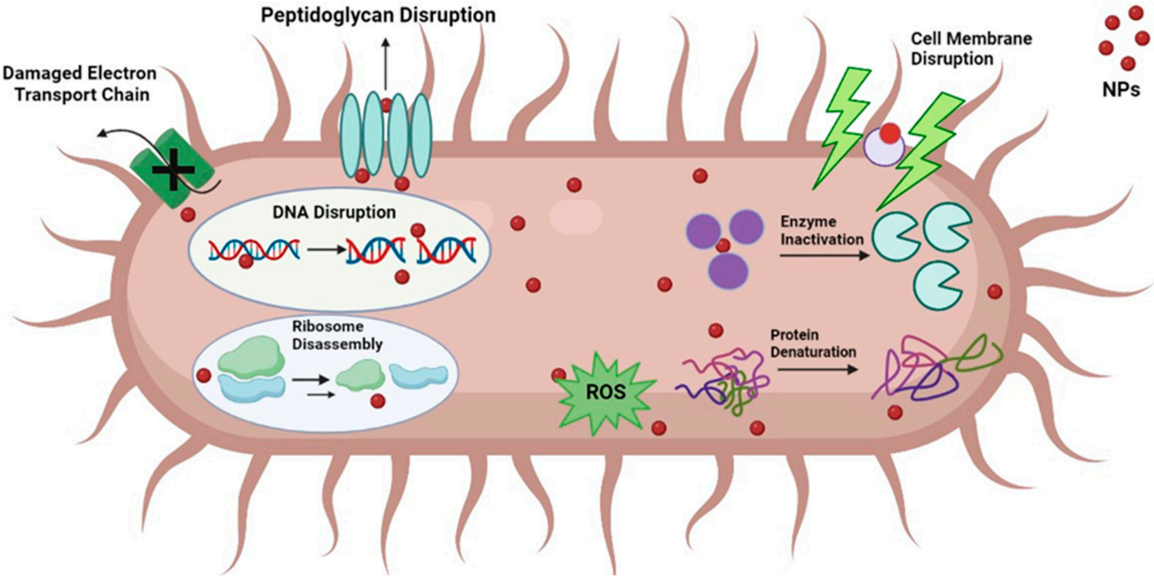

Figure 4. Mode of action of algal NPs on bacterial cell.

Studies have been carried out to explore the antibacterial properties of nanoparticles (NPs) derived from algae against various strains of bacteria. For instance, silver nanoparticles (AgNPs) that were synthesized from the brown seaweed *Padina tetrastromatica* demonstrated effective inhibition of the growth of *Bacillus subtilis*, *Klebsiella planticola*, and *Pseudomonas aeruginosa* [58]. A different study revealed that silver nanoparticles (AgNPs) with stable and colloidal shapes, created using an aqueous extract from *Caulerpa serrulata*, a type of green marine algae, had a notable ability to combat bacteria at lower concentrations. This effectiveness was observed against several strains of bacteria, such as *Shigella* sp., *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Escherichia coli* [102]. In a similar vein, promising antibacterial activity was observed in silver nanoparticles (AgNPs) created using an aqueous extract of *Pithophora oedogonia* against several bacterial strains, such as *Bacillus subtilis*, *Micrococcus luteus*, *Vibrio cholerae*, *Staphylococcus aureus*, *Escherichia coli*, *Shigella flexneri*, and *Pseudomonas aeruginosa* [103].

In addition, a notable inhibition of *Bacillus subtilis* and *Staphylococcus aureus* growth was observed in spherical gold nanoparticles (AuNPs) created using a protein extract from the blue-green alga *Spirulina platensis* [104]. The antibacterial efficacy of AuNPs synthesized from *Ecklonia cava* and *Nitzschia* was also evaluated against several bacterial strains, including *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Bacillus subtilis* [105,106]. When compared to the conventional tetracycline antibiotic, the AuNPs produced from *Stoechospermum marginatum* exhibited better antibacterial activity against *Enterobacter faecalis* [107]. Another study evaluated the antibacterial potential of AuNPs and AgNPs mediated by *Neodesmus pupukensis* against various strains of bacteria [108]. These results suggest that algae-mediated nanoparticles have the potential to be used as antibacterial agents in the future. Moreover, different types of algal strains and their in vitro antibacterial activity are displayed in Table 2.

Table 2. Different types of algal strains and their in vitro antibacterial activity.

Class	Algal Strain	NPs	Shape and Size	Test Organism	NPs Dose	Mode of Action	References
Pheophyceae	*Bifurcaria bifurcate*	CuO	Spherical and elongated; 5–45 nm	*E. aerogenes*, *S. aureus*	20 µg/mL	Disruption of DNA structure and biochemical processes	[109]
Rhodophyceae	*Galaxaura elongate*	Au	Spherical, 3.85–77.13 nm	*E. coli*, *K. pneumoniae*, *MRSA S. aureus*, *P. aeruginosa*	-	Inhibition of respiratory chain enzymes and membrane permeability	[88]
Pheophyceae	*Sargassum plagiophyllum*	AgCl	Spherical, 18–42 nm	*E. coli*	20 µg/mL	ROS generation and membrane disruption	[110]
Chlorophyceae	*Chlorococcum humicola*	Ag	Spherical, 4 and 6 nm	*E. coli* (ATCC 1105)	10 µg/mL	-	[111]
Diatoms	*Amphora-46*	Ag	Spherical, 5–70 nm	*E. coli*, *B. stearothermophilus*, and *S. mutans*	25 µg/mL	-	[112]
Chlorophyceae	*Caulerpa racemose*	Ag	Spherical and triangle, 5–25 nm	*S. aureus* and *P. mirabilis*	5–15 µg/mL	Generation of ROS and cell death	[113]
Chlorophyceae	*Ulva fasciata*	Ag	Spherical, 28–41 nm	*Xanthomonas campestris* pv. *Malvacearum*	30–90 µL	Impairment of DNA replication	[58]
Pheophyceae	*Turbinaria conoides*	Au	Triangle, rectangle, and square, 60 nm	*Streptococcus* sp., *B. subtilis*, and *K. pneumoniae*	-	-	[57]

Table 2. *Cont.*

Class	Algal Strain	NPs	Shape and Size	Test Organism	NPs Dose	Mode of Action	References
Rhodophyceae	*Gracilaria dura*	Ag	Spherical, 6 nm	*B. pumilus*	-	-	[114]
Rhodophyceae	*Hypnea musciformis*	Ag	16—42 nm	-	-	-	[115]
Rhodophyceae	*Gelidiella acerosa*	Ag	-	*Pseudomonas aeruginosa* and *Bacillus subtilis*	-	-	[116]
Pheophyceae	*sargassum myriocystum*	ZnO	Spherical, 36 nm	*S. mutans*, *M. luteus*, *V. cholerae*, *K. pneumoniae*, *N. gonorrohea*	10–40 µL	Generation of ROS and cell death	[117]
Pheophyceae	*Sargassum wightii*	Ag	Spherical, 50–100 nm	*Staphylococcus aureus*, *Bacillus rhizoids*, *Escherisia coli*, and *Pseudomonas aeruginosa*	-	-	[118]
Chlorophyceae	*Spirogyra hyalina*	Fe_3O_4	Spherical, 52 nm	*E. coli*	10–40 µL	-	[27]
Prymnesio-phyceae	*Isochrysis* sp.	Ag	Spherical, 64.47 nm	*P. aeruginosa*, *E. coli*, *S. aureus*, and *B. subtilis*	10–30 µL	Disruption of plasma membrane, inhibition of respiratory chain and cell death	[100]
Chlorophyceae	*Ulva lactuca* and *Ulva conglobata*	Ag	Spherical, 25–40 nm	*P. aeruginosa*, *E. coli*	-	-	[119]

7. Shortcomings in the Existing Research and Potential Avenues for Future Exploration

The antimicrobial mechanisms of algal NPs remain uncertain. While certain studies link their antimicrobial effects to oxidative stress or ROS generation, others associate them with the modulation of bacterial metabolism. Hence, there is a need for further investigation into the antibacterial mechanisms of NPs. The absence of standardized protocols is a constraint in the current studies that explore the antibacterial mechanisms of algal NPs. Various studies have used different bacterial strains, exposure durations, and NP properties, which hinder the comparison of antibacterial efficacy. Furthermore, there is no one technique that fulfils all the prerequisites for examining the antibacterial mechanisms of NPs. As different kinds of NPs have varying effects against bacteria, scientists often recommend a comprehensive investigation to understand their potential antibacterial mechanisms. Moreover, NPs are often tested for their ability to kill bacteria by using delicate bacterial strains for precise evaluation of their antibacterial efficacy.

A further hurdle in investigating the antibacterial properties of algal NPs is the complex configuration of the bacterial cell membrane, which complicates the complete comprehension of the interaction between bacterial cells and NPs. Moreover, there is an absence of well-established research methodologies for in vitro investigations. In vitro models have their restrictions and cannot accurately replicate the intricacy of in vivo circumstances, resulting in possible errors in determining the antibacterial efficacy of NPs based solely on bacterial cell culture studies.

Further examination is needed to clarify the mechanism by which NPs traverse the bacterial cell membrane since it remains uncertain. At low concentrations, NPs might potentially cause bacterial cell disintegration and removal of the LPS layer, resulting in the development of membrane protrusions in the shape of vesicles that adhere to NPs. This electrostatic attraction could enable NPs to penetrate the cell. Nonetheless, further investigation is required to comprehensively comprehend this process. Intracellular inhibitory mechanisms of NPs have not been extensively researched. The impact of NPs on oxidative stress is a significant area of research, and only a limited number of studies have examined how NPs influence bacterial cell gene metabolism, protein synthesis, and expression.

8. Future Explorations of Algal Nanoparticles in Different Fields

The exploration of algal-based nanoparticles holds great promise for a wide range of applications. Here are some potential future directions for their exploration:

(i) Biomedical Applications: Algal nanoparticles have shown potential in various biomedical applications, including drug delivery, imaging, and therapeutics. Future research may focus on optimizing their properties for targeted drug delivery, developing multifunctional nanoparticles for simultaneous imaging and therapy, and exploring their potential in regenerative medicine.

(ii) Environmental Remediation: Algae possess unique capabilities to absorb and remove pollutants from water and air. Algal nanoparticles can be engineered to enhance these properties and improve their efficiency in environmental remediation processes. Future exploration may involve developing algal-based nanoparticles for wastewater treatment, air purification, and soil remediation.

(iii) Agricultural Applications: Algal nanoparticles have the potential to revolutionize agriculture by improving crop growth, nutrient uptake, and disease resistance. Researchers may explore the use of algal nanoparticles as smart fertilizers, nanopesticides, or nanobiostimulants to enhance plant productivity while minimizing the environmental impact of conventional agricultural practices.

(iv) Energy Applications: Algae are known for their ability to convert sunlight into chemical energy through photosynthesis. Algal nanoparticles could be harnessed for energy-related applications, such as solar cells, fuel cells, and energy storage devices. Future exploration might involve optimizing the efficiency of algal-based materials for energy conversion and storage applications.

(v) Food and Nutraceutical Industries: Algal nanoparticles can be used as delivery systems for bioactive compounds, antioxidants, and micronutrients. Future research may focus on developing algal-based nanoparticles for encapsulating and delivering functional ingredients in the food and nutraceutical industries, potentially leading to innovative and healthier food products.

(vi) Bio-inspired Materials: Algae produce a wide range of unique materials with remarkable properties. Researchers may explore the use of algal-based nanoparticles as building blocks for the synthesis of bio-inspired materials, such as superhydrophobic coatings, self-healing materials, and biomimetic structures.

(vii) Nanosensors and Diagnostics: Algal nanoparticles can be functionalized to detect specific molecules or ions, making them potential candidates for nanosensors and diagnostic applications. Future exploration may involve developing algal-based nanoparticles for early detection of diseases, environmental monitoring, and point-of-care diagnostics.

These are just a few potential future directions for the exploration of algal-based nanoparticles. As research in this field progresses, we can expect to uncover more exciting applications and further optimize the properties and functionalities of these nanoparticles [28,98,99,120–123].

9. Conclusions

The increasing issue of bacterial resistance to multiple medications has presented a significant obstacle in addressing infectious diseases and achieving effective patient treatment. This situation has led to increased rates of morbidity and mortality worldwide. However, a potential solution lies in the utilization of algae, which are abundantly found in various habitats, for the production of eco-friendly metallic nanoparticles (NPs) on a large scale. The use of algal NPs as a substitute for antibiotics shows significant potential in addressing the emergence of multidrug-resistant bacteria. Traditional antibiotics are becoming less effective due to the development of resistance mechanisms in bacteria.

Algal NPs, on the other hand, exhibit potent antibacterial properties that can combat drug-resistant strains effectively. Algal NPs offer a sustainable and green alternative for combating bacterial infections. However, it is important to ensure that the use of algal NPs remains safe and does not induce cytotoxic effects. Comprehensive reviews of the antibacterial mechanisms of algal NPs can aid in the development of effective antibacterial formulations while minimizing potential cytotoxicity concerns. These reviews can provide valuable insights into optimizing the synthesis methods, determining appropriate dosages, and evaluating the safety profiles of algal NPs. In summary, algal NPs hold significant promise as a favourable substitute for antibiotics in addressing the challenge of multidrug-resistant bacteria. Their eco-friendly synthesis, potent antibacterial properties, and ability to combat biofilms make them an attractive option in the fight against infectious diseases. Through comprehensive reviews of their antibacterial mechanisms, researchers can develop effective and safe antibacterial algal NPs, thereby contributing to the prevention and management of bacterial infections.

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