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Potential antimicrobial effect of Microalgae: A future therapeutic approach

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Microalgae is a prospective source of bioactive compounds that can be used in biomedicine. The antimicrobial potential of bioactive substances derived from algae is still under investigation. Novel extraction strategies for algal bioactive chemicals are emerging. Microalgae can be utilized in a way that is economical for the production of nanoparticles. In this review, we reported the therapeutic potential of microalgae and microalgae-based nanoparticles against bacterial, viral, and fungal infection. Microalgae significantly contribute to the manufacturing of nanoparticles while having little to no negative side effects on the treatment of bacterial infections. Microalgae have not been thoroughly investigated in the creation of nanoparticles. Future research would be required to comprehend the precise processes of the reaction and categorize the proteins and enzymes involved in forming algal nanoparticles.

Keywords: Microalgae; Nanoparticles; Antibiotics Resistant; Therapeutics

INTRODUCTION

Pathogenic bacterial resistance to antibiotics and other medications has evolved into a clinical irritation as a result of hospital patients bringing drug-resistant bacteria with them that can spread nosocomial (Swain et al. 2017). Finding novel antibacterial chemicals has become more challenging due to pathogenic microorganisms growing more resistant to many antibiotics, negatively affecting human health (Dey et al. 2023). At least in burn and urinary tract infection (UTI) patients, empirical treatment is a direct/urgent option, and with the increase in hospitalization costs, long-term comorbidities usually occur. Additionally, because of the adaptability of the bacterial heritable exchange mechanism, drug-resistant indicators in plasmids and transposons in bacteria persist peripatetic across correlated and different taxa (Lalegerie, Lajili et al. 2019).

According to the current research progress of plant products and drug discovery, natural products are acknowledged as a significant source of compounds leading to medications against many diseases. Parallel to this, marine drug discovery, which uses blue-green algae (cyanobacteria) and other marine microbes for innovative therapies, has arisen as a comparatively alternative discipline since the 1940s. With new compounds being found every year, the amount of marine potential compounds may surpass 28,000 (Swain, Paidesetty et al. 2017, Lalegerie, Lajili et al. 2019).

Microalgae are photosynthetic entities that have been widely used as sources of biofuels, food, nutraceuticals, and vitamins. These microbes generate a wide range of bioactive substances that may have anti-microbial, anti-cancer, anti-inflammatory, and health-improving effects. The phytochemical components of microalgae, particularly the secondary metabolites, which is considered to be the major sources for many valuable bioactive substances, are primarily responsible for their biomedical qualities (Barsanti and Gualtieri, 2018, Kratzer and Murkovic, 2021, Menaa et al. 2021). Defense responses, cell signaling, and regulation of development are all impacted by microalgae bioactive peptides (Skjånes et al. 2021). Nearly every ecosystem in the world contains microalgae. They were exposed to microbial diseases including bacteria, viruses, and fungi as they evolved in extremely competitive habitats, which are grazed by a wide variety of consumers. They have to learn defense mechanisms or tolerance to survive. Due to the diversity of these mechanisms, a wide range of metabolic pathways were used to synthesize a wide range of chemicals. It seems that many of these metabolites have very particular chemical composition that are uncommon in terrestrial animals. Additionally, some of these metabolites may have complex structural makeups that make it difficult to replicate them by partial or full synthesis (Borowitzka, 1995, Sigee, 2005, Löndahl, 2014).

Microalgae are a significant and abundant source of bioactive substances with antibacterial properties. Microalgae contain a variety of antimicrobial secondary metabolites, including peptides called portoamides, flavonoids, eicosapentaenoic acid, alkaloids, and many others (Awdhesh Kumar Mishra and Kodiveri Muthukaliannan, 2022, Hassan et al. 2022). The numerous secondary metabolites found in microalgae are thought to have extraordinary biological effects. Due to its extensive variety of biological activities, including antibacterial, anticancer, antiviral, and immunomodulatory activities, bioactive phenolic compounds derived from microalgae (MBPCs) are particularly beneficial to the biopharmaceutical and nutraceutical industries (Kapoor et al. 2022).

The current work aims to present the potential effects of microalgae against bacteria, viruses and fungi with a special interest on future advancement such as with the use of nanotechnology to combat antibiotics resistant.

Antibacterial Compounds Present in Microalgae

Microalgae have long been employed for therapeutic purposes, and in the 1950s, systematic searches for their physiologically active constituents began (Amaro et al. 2011, Falaise et al. 2016a). However, over the past 10 years, substantial research has turned its attention to microalgae with the hope of discovering new chemicals that could eventually become therapeutically effective medicines (Mendes et al. 2003, Mayer and Hamann, 2005, Cardozo et al. 2007, Kellam and Walker, 1989). In the interim, it has been shown that microalgae can manufacture antibiotics: numerous microalgal extracts and/or extracellular products have shown to be antibacterial, antifungal, antiprotozoal, and antiplasmodial (Kellam and Walker, 1989, Ozdemir et al. 2004, Herrero et al. 2006, Ghasemi et al. 2004). Indoles, terpenes, acetogenins, phenols, fatty acids, and volatile halogenated hydrocarbons have all been linked to the antimicrobial activity of microalgae (Jena and Subudhi, 2019, Shaikh et al. 2022, Amaro et al. 2011). For example, the antimicrobial activity of supercritical extracts obtained from the microalga Chaetoceros muelleri were linked to its lipid composition (Mendiola et al. 2007).

Proteins, polysaccharides, polyunsaturated fatty acids (PUFAs), particularly EPA and DHA, amino acids, and antioxidants (polyphenols, flavonoids, and carotenoids) are the supreme important bioactive components of algae with standard antibacterial activity. However, due in large part to the novel types of compounds discovered in recent years, the identification of molecules directly accountable for the antibacterial potential of algae is still a comparatively undeveloped field of research (Arguelles Arias, 2011, Senthilkumar and Sudha, 2012).

Some research characterized the antibacterial substances found in the biological extracts. These bioactive substances can be pigments like phycobiliproteins or derivatives of chlorophyll, but free fatty acids make up the majority of them. Long chain fatty acids from *Scenedesmus obliquus* and short chain fatty acids from *H. pluvialis* have antibacterial action against *E. coli* and S. aureus, respectively. Polyunsaturated fatty acids from *Chlorococcus strain HS-101* and *Dunaliella primolecta* have antibacterial defenses for methicillin-resistant Staphylococcus aureus (MRSA), a bacterium that is very difficult to treat with traditional medicines and conventional antibiotics and causes thousands of deaths each year (Najdenski et al. 2013, Falaise et al. 2016a).

Numerous bioactive substances found in microalgae can help people meet their nutritional and energetic needs. The antimicrobial properties of algal lipids and fatty acids are linked to their capacity to impede the electron transport chain and oxidative phosphorylation processes in cellular membranes. This disruption results in the generation of peroxidation and auto-oxidation degradation products, ultimately leading to cellular lysis. The list of antibacterial compounds from different algae and their target bacterial pathogens given in Table. 1. By adjusting the culture conditions and applying environmental stress, it is possible to change the biochemical makeup of microalgae and get the microorganisms to create large concentrations of a certain bio compound. Microalgae can also be grown in areas where there is no worry about land use change because they don't require arable land. Microalgae bioactive substances provide the population's needs for nutrients and energy while promoting health to ward off chronic diseases (da Silva Vaz et al. 2016).

Therapeutics effect of Microalgae against Pathogenic bacteria

Microalgae have a lot of potential as antibacterial agents, but nothing has been done to advance them from the characterization stage into the biotechnology stage. The capacity of microalgae to produce response of bioactive secondary metabolites to the environment cues presents a difficulty when screening them for antibacterial activity. A thorough scientific approach is needed to find promising strains with strong antibacterial activity and to promote the research progress of antibacterial agents for microalgae. As more microalgae are tested and compounds are discovered, the likelihood of successful expansion and commercialization of microalgae antibacterial agents drugs will rise (Stirk and van Staden, 2022).

Table 1. Antibacterial compounds from different algae and their target bacterial pathogens.

Antibacterial compound	Microalgae	Target bacterial pathogens	References
Pigments	*Anabaena cylindrical Chlorococcum humicola, Spirulina platensis, Nostoc*	*E. coli, S. typhimurium*, *K. pneumoniae*, *V. cholerae*, *S. aureus*, *B. subtilis, Streptococcus* sp., *Pseudomonas* sp., *Bacillus* sp., *Staphylococcus* sp., *E. coli, Enterobacteria aerogens*	Goud et al.(2007). Bhagavathy and Sumathi, (2010). Fan et al. (2013).
Fatty acids and Lipids	*Dunaliella salina*, *Haematococcus pluvialis*, *Phaeodactylum tricornutum, Chaetoceros muelleri, Spirulina platensis*	*Escherichia coli, Staphylococcus aureus,* MRSA, *Listonella anguillarum, Lactococcus garvieae, Vibrio* spp	Xue et al. (2002). Santoyo et al. (2009)
Carbohydrates	*Anabaena sphaerica*, *Chroococcus turgidus*, *Oscillatoria limnetica, S. platensis, Porphyridium cruentum*	*E. coli, S. typhimurium, S. faecalis*	O’doherty et al. (2010) Muthulakshmi et al. (2012).
Polyphenols	*Anabaena sphaerica*, *Chroococcus turgidus*, *Oscillatoria limnetica* and *Spirulina platensis*	*Salmonella typhi, Streptococcus*, *E. coli* and *Staphylococcus aureus*	Gao, D., & Zhang, Y. (2010) Klejdus et al. (2010). Sivadasan et al. (2014).

The bioactive metabolites derived from microalgae species, possessing therapeutic potential, have garnered significant attention This keen interest aims to facilitate the development of more promising therapeutic agents for addressing pressing global health issues, including infectious diseases and bacterial infections. (Wong et al. 2022)

Ongoing research is actively investigating the multitude of bioactive constituents within microalgae species. Recent findings have revealed diverse therapeutic prospects associated with microalgae. (Koyande et al. 2019).

Thereafter, numerous investigations were conducted to find chemicals with antibacterial action in microalgae, either to create novel medications to treat bacterial infections or to create food additives (Bhagavathy, S., Sumathi, P., & Bell, I. J. S. 2011). In order to evaluate potential antibacterial activity of Inhibitory effects of different microalgae extracts on pathogenic and foodborne bacteria, extensive screening programs have been carried out. It has been demonstrated that several microalgal species from various taxonomic groups has strong antibacterial action present against both gram positive and gram-negative bacteria in both freshwater and marine environments, as well as in soil (Pane et al. 2015). Due to the fact that screening studies occasionally comprise hundreds of distinct microalgae having the strongest antibacterial activity or the broadest spectrum of action. These investigations suggested that the synthesis of antibiotics depends greatly on the microalgal species (Bhagavathy et al. 2011, Pane et al. 2015, Ördög et al. 2004, Falaise et al. 2016b).

Microalgae role in controlling biofilm related quorum sensing.

Nosocomial microorganisms that are adhered to surfaces in biofilms, where infectious illness is caused, are the principal cause of nosocomial infections. Microbial populations that are surface attached are unharmed in the extracellular polysaccharide matrix they have generated. To survive under varied stresses and environmental circumstances, resistant bacteria use a biofilm-forming mechanism (Donlan and Costerton, 2002). Chronic and recurrent infections are brought on by bacteria that develop biofilms because they can withstand extremely high concentrations of antimicrobial substances (Lewis, 2008, Lebeaux et al. 2014). According to Costerton et al. (2003) and Bjarnsholt et al. (2009), biofilm-forming bacteria frequently play a role in the development of severe infections that result in tissue damage and chronic inflammations. In comparison to planktonic cells, plasmids (extracellular DNA) are exchanged between bacterial cells more often during biofilm (Costerton et al. 2003, Bjarnsholt et al. 2009, Aguila-Arcos et al. 2017, Wang et al. 2010).

After developing mature biofilms, the bacteria developed the resistance to these antimicrobial chemicals. The dose needed to inhibit biofilm formation for some classes of antibiotics or antimicrobials may be significantly higher than the actual concentration needed to inhibit planktonic cells for the same microorganisms (Høiby et al. 2010, Nickel et al. 1985, Aslam, 2008).

Quorum sensing controls the development of biofilms and virulence determining factors, which increases the pathogen's resistance to antibiotics. Cell-cell communication between microorganisms is made possible by an increase in the population density of microbial cells, which leads to quorum-sensing signaling. It controls the virulence-regulating elements that are produced as well as the development of biofilms (Mo et al. 2009, Paluch et al. 2020). There are three types of autoinducers: furanosyl borate diester, acylated homoserine lactones, and peptides. The Gram-negative bacteria utilise acylated homoserine lactones in the regulatory mechanism (Waters and Bassler, 2006, Waters and Bassler, 2005, Galloway et al. 2011).

A heterogeneous mixture of polar and non-polar molecules makes up crude microalgae extracts . Alkaloids, phenolic compounds, and flavonoid families are a few secondary metabolites that microalgae also create. These chemicals have antibacterial characteristics and prevent bacteria from forming biofilms (Koo and Jeon, 2009). According to Abreu et al. (2012), many kinds of secondary metabolites can permeate the cell membrane, preventing the formation of biofilms or facilitating the entry of more molecules into the cells (Abreu et al. 2012). Marine organisms are a valuable source for the creation of novel antibiofilm chemicals because they prevent the growth of biofilm in different bacterial species (McClean et al. 1997, Bauer and Robinson, 2002, Saurav et al. 2017). The synthesis of alarmone is one method by which the severe response inhibition process of the antibiofilm action is carried out (Antunes et al. 2019).Additionally, marine metabolites have the QSI impact by lowering the pathogenic bacteria's resistance pattern and suppressing the development of virulence factors, enhancing antimicrobial sensitivity (Saurav et al. 2017, Lauritano et al. 2016).

Marine species produce natural substances or metabolites that have anti-quorum-sensing properties. It was possible to collect bioactive compounds from a variety of marine animals, including bacteria, seaweed, sponges, macroalgae, and microalgae (Dobretsov et al. 2009, Dobretsov et al. 2011). These compounds were then examined for their ability to suppress marine bacteria's quorum-sensing-regulated biofouling. Because they may be manufactured in greater amounts via bioprocess technology approaches, microalgal extracts can suppress the development of biofilm and quorum-sensing mechanisms (Desbois et al. 2009, Desbois et al. 2010, Desbois and Smith, 2010). According to research by Desbois et al. polyunsaturated fatty acids (PUFA) extracted from marine species have antibiofilm activity (Desbois et al. 2009). According to Blunt et al. , about 1340 novel metabolites from the MarinLit database (Marine Natural Products Database) were efficient against bacterial infections, high cholesterol, cancer, and viral illnesses (Blunt et al. 2010, Blunt et al. 2017).

The antibiofilm effect of cyclic peptides from the *Phormidium sp*. is demonstrated against a variety of marine bacteria, such as *Cobetia marina, Halomonas aquamarina, and Pseudoalteromonas atlantica*. 2019 (Antunes et al. 2019, Olsen et al. 2010). Chlorella vulgaris, a freshwater green microalga, produces a wide range of bioactive substances with dietary and medicinal benefits (Zheng et al. 2012). Chemicals taken from the microalgal *species L. danicus* and *L. aporus* prevent the bacterium *S. epidermidis* from forming a biofilm. (Lauritano et al. 2016). Gram-positive bacteria are more resistant to pepsin hydrolysate's antibacterial effects than Gram-negative bacteria (Tejano et al. 2019, Khalid et al. 2010).

Antiviral effects of Microalgae

Since the SARS-CoV-2 epidemic in 2020, which caused a significant number of deaths and the collapse of the economy, science has stayed concentrating on the study of antivirally dynamic substances generally. Microalgae, a type of photosynthetic organism, are well-known to be a major source of bioactive secondary metabolites; this fact, beside with the ability to grow to extremely high biomass levels without incurring high energy costs, makes microalgae deserving of consideration in the hunt for novel molecules with antiviral properties (Carbone et al. 2021). In one of the earliest investigations on the antiviral action of microalgae, Umezawa et al. demonstrated that a Chlorella pyrenoidosa extract containing acid polysaccharides inhibited the vesicular stomatitis virus (VSV) in mice (Umezawa and Komiyama, 1985). Some methanol extracts of spirulina or ankistrodesmus convolotus shown anti-Epstein Barr virus (EBV) activity by suppressing several proteins linked to the viral lytic cycle, including zebra, ebna, and lmp1.

Table 2: Studies showed the antiviral activity of various algal strains.

Microalgae species	Bioactive compounds	Antiviral activity	References
Ecklonia cava	Phlorotannin	Against +HIV	Ahn et al. (2007)
Grateloupia filicina	Sulphated polysaccharides	Against HSV	Wang et al. (2007)
Sphaerococcus coronopifolius	Sulphated Polysaccharides	Against Influenza, Herpes, HIV	Bouhlal, R et al. (2011)
Spirulina platensis	Calcium-spirulan (Ca-SP)	HIV1, HIV2, HSV1, HSV2	Lee et al. (2001)
Navicula directa	Polysaccharide	HSV1 & 2, Influenza A virus	Lee JB et al. (2001)
Cryptomonads	Allophycocyanin	Enterovirus 71	Shih et al. (2000)
Chlorella autotrophica	Sulfated polysaccharides	VHSV, ASFV	Fabregas et al. (1999)

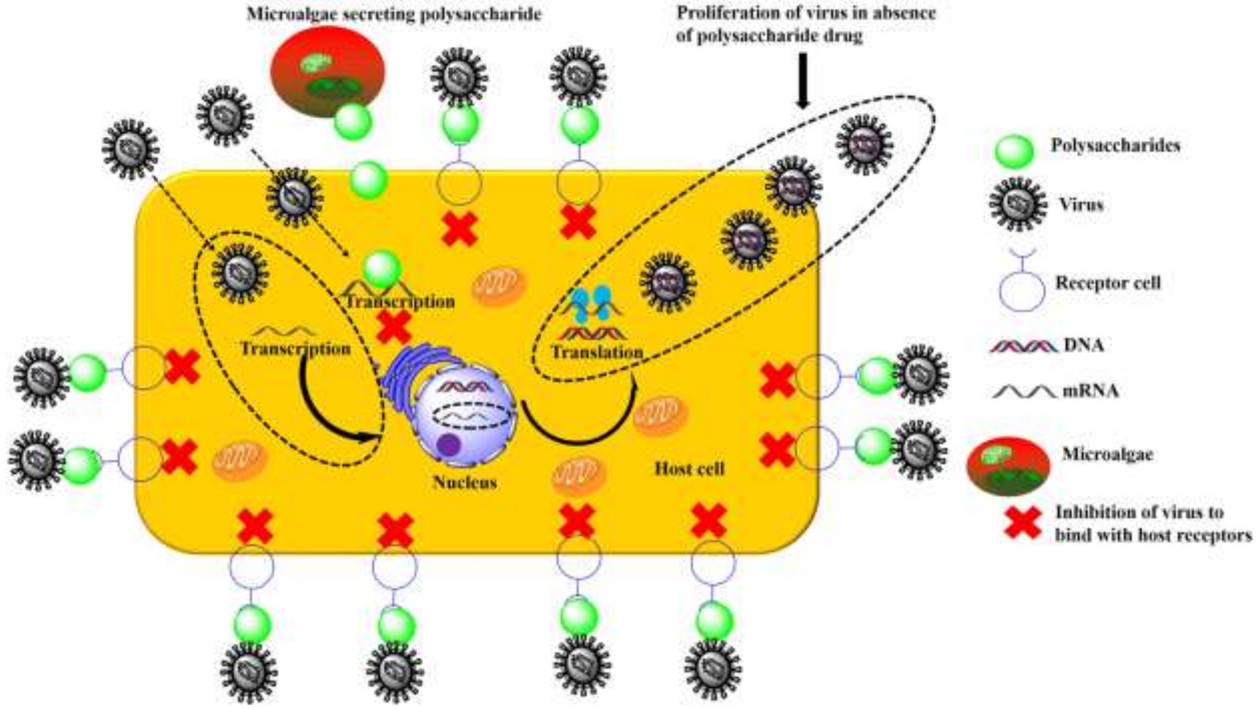

Figure:1 The mechanism by which polysaccharides derived from microalgae inhibit the attachment of the virus to the host cell and its subsequent transcription (Dehghani et al. 2022)

Unknown phycobiliprotein pigments are likely responsible for this action. YHV, a Roniviridae family single-stranded RNA virus, that infects prawns, is expressed using double-stranded RNA using the green microalga *Chlamydomonas reinhardtii* as a carrier. Animals are introduced orally to it.

These bioengineered microalgae were used to treat organisms, and they are resistant to virus infection. (Kok et al. 2011, Somchai et al. 2016). All things considered, we think that microalgae might be an effective alternative biosystem for the manufacture of S and human ACE2 glycoproteins for the treatment of COVID-19 infected patients. Additionally, these bacteria have a high potential for edible transfer of the glycoproteins they make, precisely into the various SARS-CoV-2-infected gastrointestinal tract regions. This quick, uncomplicated, inexpensive, and straightforward technique can drastically lower the price of ACE2 therapy and the COVID-19 vaccine every treatment term (Dehghani et al. 2022). The antiviral mechanism of algal polysaccharides includes the suppression of virus transcription and replication, achieved through the direct interaction of sulfated polysaccharides with viral replication enzymes.

All tested influenza virus strains, even those with resistance to influenza drugs oseltamivir and amantadine, were strongly inhibited from infecting cells through euglena extract. The cycle of virus replication was not impacted by Euglena extract, according to a time-of-addition experiment, and cell pretreatment or sustained treatment of infected cells decreased the virus titer. As a result, relatively than directly combating the influenza virus, euglena extract may trigger the host cell resistance mechanisms.

Table 3: Antifungal Properties of Selected Compounds from Microalgae

Algae	Antifungal compound	Fungal agent	Reference
Laurencia composita	Laurecomin B	*Colletotrichum lagenarium*	Liang and Gadd. (2017)
Laminaria	Laminarin-based formulation Vacciplant	*Zymoseptoria tritici*	de Borba et al. (2022)
Laurencia okamurai	Seco-laurokamurone, laurepoxyene, 3β-hydroperoxyaplysin	*Cryptococcus neoformans, Candida glabrata,*	Washida, K et al. (2006)
Eisenia bicyclis	Fucofuroeckol-A	*Candida albicans*	Kim and Kang. (2018)
Ulva fasciata	Phenolic, flavonoid contents	*Penicillium digitatum, Penicillium expansum and Penicillium italicum*	Fayzi et al. (2022)
Ecklonia cava	Dieckol	*Trichophyton rubrum*	Sung and Lee (2010)
Arthrospira platensis	Ethanol, Methanol, Ethyl acetate, Acetone	*Candida albicans, Malassezia furfur, Trichophyton rubrum*	Gheda et al. (2023)

Additionally, it was shown that Euglena extract's antiviral properties was influenced by a number of minerals, particularly zinc (Nakashima et al. 2021). Microalgae have garnered significant attention as promising sources of antiviral agents (Borowitzka, M. A. 1995). Several notable examples are presented in Table 2."

Antifungal Activity of Microalgae

Regarding the antifungal properties of microalgae, a significant study revealed the antifungal potential of *Halimeda tuna* against a variety of foodborne pathogens, including nine fungi: *Alternaria alternaria, Candida albicans, Aspergillus niger, Trichophyton mentagrophytes, Trichophyton rubrum, Penicillium spp.,* and *Rhizopus spp*. In that investigation, the ethanolic, methanolic, and chloroform seaweed extracts all had a minimum fungicidal concentration (MFC) of 500 g/mL, but the water-based extracts had an MFC value extending from 250 to 500 g/mL. Methanol extract from *Halimeda tuna* was the most efficient against fungi, and the efficacy of the extracts from *Halimeda tuna* was remarkably significant against *A. niger*, *A. flavus*, *A. alternaria, C. albicans*, and *E. floccosum* (Pina-Pérez et al. 2017). Chlorella vulgaris aqueous biomass extract showed more antifungal efficacy than antibacterial activity. Ulva sp. and Chlorella sp. cell extracts have been shown to have antifungal activity in vitro, according to published research (Vehapi et al. 2020). The fact that the entire aqueous extract showed lesser or no antifungal activity suggests that proteins and polypeptides were accountable for the antifungal activity. With MIC values of 16.25 mg/mL, the protein portion that was separated from the *C. vulgaris* biomass showed strong antibacterial action against *L. plantarum* and *S. epidermidis* (Zielinski et al. 2020). The concomitant rise in fungal infections has prompted the exploration of novel and safer agents for the management of fungal infections (Sánchez et al.2008) with several noteworthy outcomes involving microalgae detailed in Table 3."

Use of Microalgae based nanoparticles as a therapeutic approach.

Microalgae possess a notable capacity for the sequestration of heavy metal particles and their subsequent conversion into diverse functional materials, rendering them a favorable option for the production of various nanomaterials, particularly metal nanoparticles. Therefore, algae are regarded as model organisms for the synthesis of such nanomaterial (Fawcett et al. 2017). Gold nanoparticles (AuNPs) produced using various strains of microalgae exhibit diverse biologically active properties, including antibacterial, anticoagulant, and antifouling activities (Khalil et al. 2014).

Gold nanoparticles (AuNPs) have demonstrated potential as efficient drug exporters for specialized medical care. The low toxicity of AuNPs is the initial benefit of employing them. Spherical AuNPs with a diameter of 10–18 nm were intravenously administered in a variety of dosages, and mice showed no morphological alterations, renal poisonousness, or hematological interferences. Without any sign of tissue injury, AuNPs have a tendency to assemble in particular organs that include the liver, spleen, and kidney. It is possible that certain body parts can be treated with non-malignant targeted therapy by properly functionalizing AuNPs because they appear to be easily integrated into organs (Lasagna-Reeves et al. 2010).

A prior work shows that functionalizing gold nanoparticles with microalgal peptides is a successful process. It has been demonstrated that the successful strategy for increasing peptide protection involves employing AuNPs as peptide carriers for microalgae. Their research provides a model for developing microalgae-AuNPs systems, which may be useful for a variety of biological and industrialized applications, in addition to catalysis, image enhancement, and sensing. (Torres-Díaz et al. 2022).

Algae are considered to be ideal candidates for the biosynthesis of nanoparticles because of their capacity to accumulation of metals and reduction of metal ions. As a result, they are referred to as "bio-nano factories" since the process uses dry biomass, both living and dead for the process of creating metallic nanoparticles (Priyadharshini et al. 2014).

Table: 4 List of different kind of nanoparticles produced by different algal strains

Algal Strain	Type of NPs	Shape and Size	References
Turbinaria conoides	Ag	Spherical, 96 nm	Rajeshkumar et al. (2012)
Gilidiella acerosa	Ag	Spherical, 18–46 nm	Dahoumane et al. (2017)
Padina tetrastromatica1	Ag	Spherical, 4 nm	Bhuyar et al. (2020)
Spirulina platenesis	Au	Monodispersed and spherical, 2–8 nm	El-Sheekh, M et al. (2022)
Oscillato riawillei	Ag	Spherical, 10–25 nm	Ali et al. (2011)
Nostoc ellipsosporum	Au	Decahedral and icosahedron, 20–40 nm	Parial et al. (2016)
Gracilaria edulis	Ag	Spherical, 12.5–100 nm	Pugazhendhi et al. (2018)
Chondrus crispus	Au	Spherical and polyhedral, 30–50 nm	Castro, L. et al. (2013)
Sargassum muticum	ZnO	Hexagonal, 30–57 nm	Azizi, S. et al. (2014)

Gold (Au), silver (Ag), and other metallic nanoparticles have been synthesized both intracellularly and extracellularly in Cyanophyceae, Chlorophyceae, Phaeophyceae, and Rhodophyceae algae and employed as nanomachines. Furthermore, there has been extensive recent investigation into the biosynthesis of gold nanoparticles (AuNPs) facilitated by green microalgae, as detailed in Table 4

Algae provide a desirable substrate for the production of different nanomaterials because their cell extracts contain bioactive compounds, such as pigments and antioxidants that function as biocompatible reductants. Environmentally safe silver nanoparticles effectively prevent the growth of bacteria by inducing bactericidal action against Gram-negative and Gram-positive pathogens that form biofilms. (Mukherjee et al. 2021).

In a prior study, it had been discovered that colloidal-shaped, robust silver nanoparticles demonstrated significant antibacterial action against *Shigella* sp., *S. aureus*, *E. coli*, *P. aeruginosa*, and *Salmonella* Typhi at lesser concentrations. They were generated from green marine alga *Caulerpa serrulate* aqueous extract. At a 50 µl silver nanoparticle solution, *E. coli* exhibited the highest inhibition zone (21 mm), but *S. typhi* ensured the least inhibition zone (10 mm) (Aboelfetoh et al. 2017). Researchers have examined the antibacterial performance of nanoparticles produced from algae and effective against several bacterial species *P. aeruginosa*, *Klebsiella planticola*, and *Bacillus subtilis* were all efficiently inhibited in their growth by silver nanoparticles produced derived from brown seaweed *Padina tetrastromatica* (Sangeetha et al. 2012). Previously, study documented the AgCl-NPs are produced biogenically from the green microalga *C. vulgaris* The AgCl-NPs described here could be used as antimicrobials for use in textiles, food packaging, surgical equipment, and other commercial and medical applications. They demonstrated high bacterial toxicity against pathogens of both the Gram-positive and Gram-negative varieties. AgCl-NPs are a possible new accumulation to the group of derived products from microalage having antibacterial activity (da Silva Ferreira et al. 2017). The mechanism of action of algal nanoparticles on bacterial cells is depicted in Figure 3. Graphical abstract is presented as Figure 4.

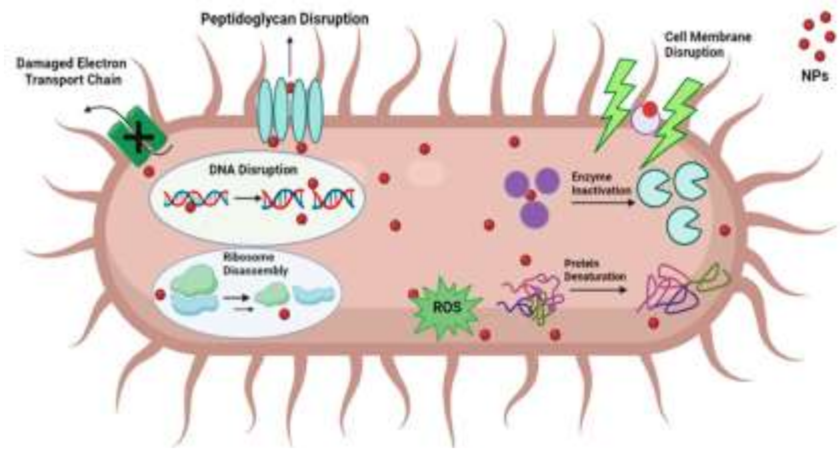

Figure: 3 Mode of action of algal NPs on Bacterial cell (Dehghani et al. 2022)

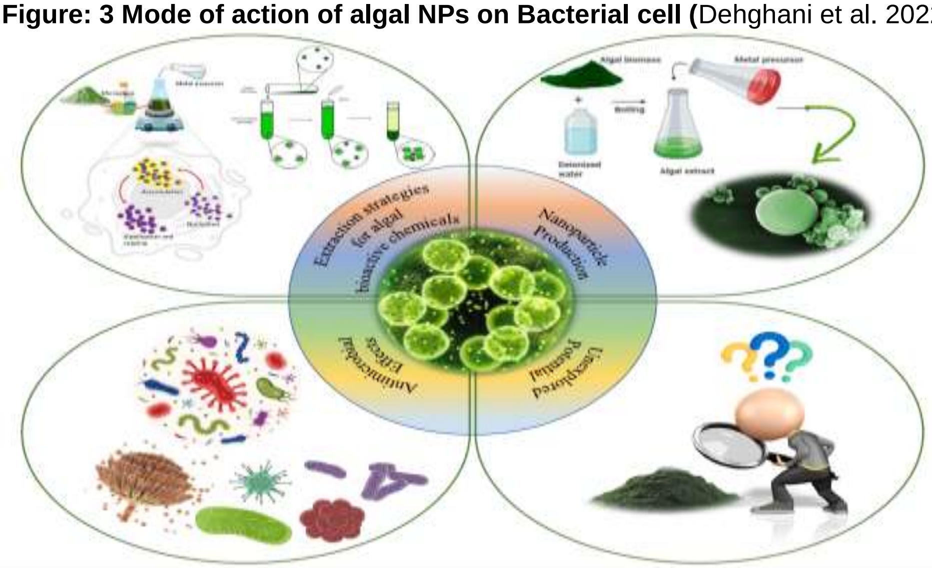

Figure 4: Graphical abstract

CONCLUSIONS

The growing challenge of bacterial resistance to multiple medications has become a substantial impediment to addressing infectious diseases and ensuring effective patient treatment. This circumstance has resulted in elevated levels of morbidity and mortality on a global scale. Yet, a viable approach involves tapping into the abundant presence of algae in diverse ecosystems to scale up the production of environmentally friendly metallic nanoparticles (NPs). Conventional antibiotics are losing their efficacy as bacteria evolve resistance mechanisms. In contrast, nanoparticles derived from algae demonstrate strong antibacterial properties capable of effectively combating drug-resistant strains.

Microalgae significantly contribute to the manufacturing of nanoparticles while having little to no negative side effects on the treatment of bacterial infections. Microalgae have not been thoroughly investigated in the creation of nanoparticles. Future research would be required to comprehend the precise processes of the reaction and to categorize the proteins and enzymes involved in the creation of algal nanoparticles.

Using microalgae as antimicrobial agents is still in the beginning phases, although they represent a promising source of bioactive compounds. It is necessary to discover new antibiotics that do not cause microbial resistance and safe for the ecosystem in the context of maintainable aquaculture. By conducting thorough examinations of their antibacterial mechanisms, researchers can formulate potent and safe algal nanoparticles with antibacterial properties, thus making a valuable contribution to the prevention and treatment of bacterial infection. The effectiveness of different microalgal compounds in contradiction of bacterial infections with resistance is highly encouraging, and there is no doubt that their use and exploitation will increase.

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Institutional Review Board Statement

This review article does not involve any primary research with human subjects, and therefore, no interaction, data collection, or analysis with human participants occurred in the preparation of this review. As such, institutional review board approval was not sought for this study. All information presented is derived from publicly available and previously published literature, and confidentiality and privacy of individuals are maintained in accordance with ethical standards.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the data is included in the article/Supplementary. Material will be available on demand.

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AUTHOR CONTRIBUTIONS

Shahid Mehmood [SM] Conceptualization, identification of key literature, and overall manuscript design.
Shuhao Huo [SH]: In-depth analysis and synthesis of reviewed material, contributing to critical discussions.
Santosh Kumar [SK]: Writing and organization of specific sections, ensuring clarity and coherence.
Ameer Ali Kubar [AAK]: Revision and refinement of language, enhancing overall readability.
Asif Mahmood [AM]: Coordination of collaborative efforts, managing references, and formatting.
Shama [S]: Final review, providing valuable feedback, and overseeing the submission process.
Feifei Zhu [FZ]: Conceptualization, Resources, Writing-review & editing, Supervision, Project administration

Conflict of interest

The authors declared that present study was performed in absence of any conflict of interest.

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