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ORIGINAL PAPER

Microalgal potential for sustainable aquaculture applications: bioremediation, biocontrol, aquafeed

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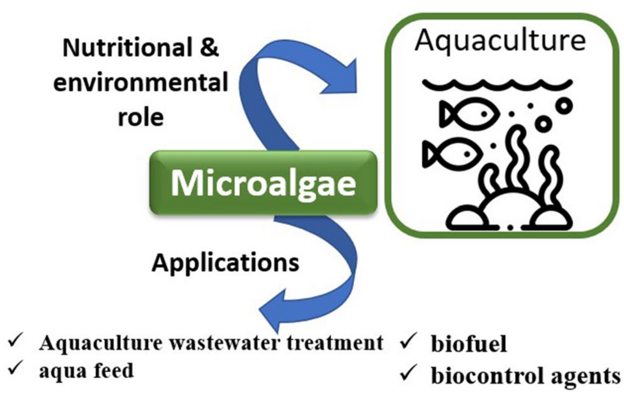
Abstract
Aquaculture has an important role in the global food market and aquatic organisms are a great reservoir of wholesome nourishment concomitantly addressing the issues of malnutrition in developing nations. The increased fish demand calls for exploring new avenues in aquaculture that include strategies for better aquaculture water management, suitable aquafeed that facilitates fish health and are rich in antioxidants, antimicrobials to ensure less motility and accelerated productivity. Microalgae possess all the qualities that qualify them to ideal sustainable aquafeed as they are rich in protein and carbohydrate, easily digestible, appetizing, and provide essential amino acids, pigments, carotenoids, vitamins, polysaccharides, and omega-3 fatty acids. The growth of algae in aquaculture wastewater leads to efficient remediation preventing eutrophication and the nutrients present in the water generate algal biomass, which can act as biocontrol agents to combat the fish pathogenic microbes like bacteria, fungi, and viruses. This review highlights the multifaceted role of microalgae in aquaculture. Exploring promising microalgae strains for aquaculture can provide viable, sustainable, and cost-effective solutions including better aquafeeds promoting aquatic health and efficiently remediating the diverse aquaculture wastewater.

Graphic abstract



Keywords Aquaculture · Aquafeed · Biocidal · Microalgae · Nutraceuticals

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Introduction

Aquaculture is one of the fastest-growing industries and even three times faster than the land animal industry, which supply feeds about 47% of human fish consumption (Ansari and Gupta 2019). This growing industry improves the economic condition due to its high global demand and helps to reduce hunger, poverty, etc. It is reported that 4.8 billion pounds are earned annually by Americans from seafood and 90% of fish imported from China in the USA (Healey et al. 2016). However, there are some challenges associated with the increasing aquaculture production, and pollution is one of them along with high larval motility (Xing et al. 2018). To overcome this problem, the practice of eco-friendly fish farming is in use; where microalgae can be a promising solution owing to their extraordinary wastewater remediation potential and their potential as natural fish feed (Bhattacharjya et al. 2021).

Algae are photosynthetic organisms; they are unicellular and multicellular organisms and ubiquitous in nature which are known as the primary producer and provide food for many aquatic animals (Brown and Blackburn 2013). The most important algae are belonging to Chlorophyceae (green algae), Rhodophyceae (red algae), Bacillariophyceae (diatoms), and Phaeophyceae (brown algae) class. Algae can also be divided into macroalgae and microalgae. Macroalgae (seaweeds) are multicellular, and they are very long and extend for more than a few meters long (Markou et al. 2012) while microalgae are single-celled, microscopic plants present in freshwater and marine water (Brown and Blackburn 2013). Most of the microalgal species are autotrophic but some of the species are heterotrophic such as *Polytoma* sp. and *Polytomella* sp. and having degenerated chloroplast (Talero et al. 2015).

Microalgae known as the earliest life form on the earth acclimatize themselves as well as their metabolism in several environments. Microalgae have a high growth rate under appropriate conditions, and they can grow in different wastewater or sewage water (Han et al. 2019). Microalgae are rich in nutrients (protein, carbohydrate, and lipids) and they are considered as the base of the food chain in aquaculture (Marella et al. 2020). They are used as food supplements by aquaculture organisms and all stages of bivalve mollusk, and the larval or juvenile stages of fish eat the microalgae (Brown and Blackburn 2013). It is reported that microalgae are also a rich source of vitamins and minerals like vitamin A, B1, B2, C, and E folic acid, magnesium, iron, iodine, calcium, etc. (Sathasivam et al. 2019), and all these qualities make them beneficial for consumption, thus, they are reducing the dependence on the traditional feed materials that may not have sufficient nutrient and growth rate on aquatic organisms (Shah et al. 2018). Microalgae use sunlight, nutrients, and carbon dioxide or carbonate for their growth and lipids synthesis (Sirakov et al. 2015). By fixing CO_2, they can transform solar energy into chemical energy which is more efficient than any land plant (Sathasivam et al. 2019). Microalgae as aquatic food are getting popular due to their high nutritional values and health benefits. They also produce high biomass and oil content under favorable conditions which make them more desirable for biofuel production and other useful products (Sirakov et al. 2015). Apart from lipids, microalgae are also rich in protein, pigments, and carbohydrates which is essential for good health, for example, protein or pigments are used in the pharmaceutical industry for the treatment of specific diseases while carbohydrates used in the fermentation process and long-chain fatty acids are used as health supplements (Chew et al. 2017). The bioactive compounds derived from microalgae have a broad range of biological activities such as antibacterial, antifungal, antiviral, anti-neoplastic, antifouling, antioxidant, anti-inflammatory, anticoagulant, and anti-enzymatic (Tiwari et al. 2021).

In the future, the aquaculture sector provides more possibilities for enhancing the productivity of diverse aquatic products (prawn, fishes, etc.) as the aquaculture sector holds immense potential and much focus is required for enhanced productivity of diverse aquatic products such as prawns and fish (Han et al. 2019). Therefore, more research and investigation are required to get the best suited and productive results. Since the demand of aquatic products is rising across the globe hence, the challenges are bound to happen and must tackled judiciously. Modulated aquafeed is the sustainable solution that would significantly improve the growth, quality, and productivity of aquatic species. In this context, microalgae play a major role to feed aquatic animals, contributing toward accelerating their productivity. Another application of microalgae is that they are used as immunostimulants as they improve the immune system and the survival rate of larvae. It is reported that in Rohu fish, *Euglena viridis* works as an antibacterial agent against *A. hydrophila* (Shah et al. 2018).

Microalgae play an important role in wastewater remediation, by removing carbon, nitrogen, phosphorus, and heavy metals from the aquatic environment (Marella et al. 2020). Microalgae like *Chlorella*, *Nitzschia*, and *Scenedesmus* are present in the highly polluted wastewater, apart from that other species like *Cyanophyta coccal*, *Dactylococcopsis* sp., *Microspora*, etc., used to treat the waste of fish in the water while *Teilingia* sp., *Anabaena* sp. *Pinnularia* sp., and *Nitzschia* sp. help to treat slaughterhouse wastewater (Salces et al. 2019). So, the use of microalgae in aquaculture wastewater supports the ecosystem as they are established as primary producers, provide 80% or more oxygen, and provide food for aquatic organisms. It has been recorded that in the year of 1990–2010 the aquaculture industry grew by 7.8% than dairy, pork, poultry, grains, and beef industry which exceeded only 1.4%, 2.2%, 4.6%, 1.4%, and 1%, respectively. Thus, the use of microalgae is instrumental in fulfilling sustainable development goals (SDGs) by reducing hunger, poverty, and giving weightage to small businesses, and maintaining a healthy environment (Troell et al. 2014). Singh et al. (2021) reported that the total nitrate, COD, and total phosphorous were removed from wastewater by using *Chaetoceros* and *Isochrysis*. Thus, the sixth SDG can be

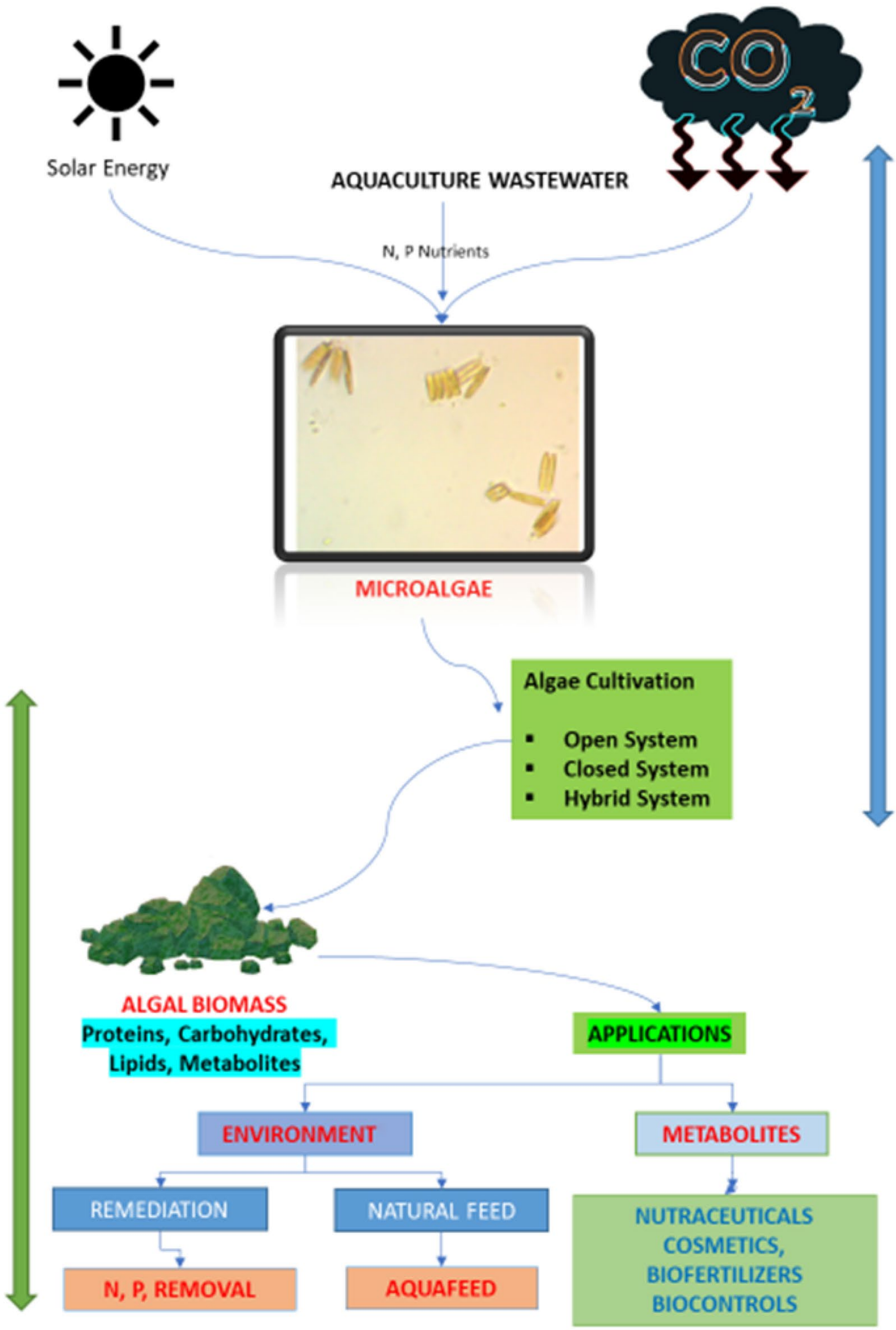

Fig. 1 The diverse applications of aquaculture wastewater generated algal biomass

achieved by microalgae ensuring clean water and sanitation (Singh et al. 2021). Figure 1 describes the diverse application of microalgae in aquaculture wastewater remediation and application of algal biomass in the environment and a plethora of applications.

This review elaborates the multifaceted applications of microalgae in aquaculture through wastewater remediation, nutritional potential as aquafeed, biocontrol agents in combating aquatic pathogens, and other prospects.

Outlook for circular bioeconomy

The circular bioeconomy is ideal for the production and consumption of bio-based products, wherein suitable sources are being reused, repaired, and recycled. Algae are beneficial for the circular bioeconomy as they do not require very compound media; they only just need light, basic nutrients to grow and do not require arable land, excess water even they convert atmospheric carbon dioxide into high nutrient products. This provides a better circular bioeconomy via the general circular aquaculture industry. Microalgae can be cultivated in different wastewater like sewage wastewater, aquaculture wastewater, dairy wastewater, brewery wastewater, etc., as a source of nutrients for their growth (Marella et al. 2020; Tan et al. 2020), and there is a wide range of high-value products generated from algal biomass. The utilization of microalgae can be very effective as a source of renewable energy as there is no need for farming land; they can grow in very less amount of water or area, not required expensive nutrient media, and have a high CO_2 mitigation rate. Biodiesel production by using microalgae is one of the best way as it has high oil production because of high lipid content and it can be cultivated or managed easily (Amit and Ghosh, 2018). And it is known that microalgae can produce more than 60% of oil content by dry weight biomass.

In microalgae, lipids are crucial metabolites and important for the growth of aquatic organisms. The microalgal lipids retain both essential and nonessential fatty acids. Microalgal species and their growth condition determined the types of lipid and their content (Ansari and Gupta 2019). For the lipid extraction from microalgae, high temperature and use of organic solvents (ethanol, acetone) are required and numerous techniques are used for lipid extraction such as solvent extraction, ultrasonic extraction, and microwave-assisted extraction (Chew et al. 2017).

Among that, wastage of food is generating a huge amount of bio-waste all around the world. And this may be generated during manufacturing, handling, packing, and consumption. Wastage of food is the big problem; this food contains carbohydrates, lipid, and proteins that can degrade into a simple form such as glucose, fatty acid, and amino acid, respectively. To manage the wastage of food, the waste food can be converted into bio-fertilizer, biodiesel, and other useful things by bioprocessing, where algae play a promising role. Algae utilize the waste food and wastewater as their nutrients. When algae or microalgae grow in the wastewater, it gives a maximum quantity of lipids and biomass. Reported that *Chlorella pyrenoidosa* and *Schizochytrium mangrovei* when cultivated in canteen waste like vegetable, rice, and meat, etc., produce more lipids while *Chlorella sorokiniana* give approx. 23% of intracellular lipid when it cultured in food and municipal wastewater (Dahiya et al. 2018), and another report where *Chlorella minutissima* was cultured in aquaculture wastewater produce 46.4% (w/w) of lipid and have maximum biomass productivity (Paw et al. 2019). Thus, microalgae give the sustainable goal by cultivating them in different wastewater and waste food as a source of nutrients; that is the solution of circular bioeconomy over environmental waste and agriculture by lowering the greenhouse gas emission, deforestation, and nutrient pollution (Dahiya et al.2018).

Microalgae are the primary producer in the food chain for aquatic animals that are rich in nutrients. The carbohydrates, protein, and lipid content are dependent on the algal species and the production of hormones, pigments, and secondary metabolites also depends on the algal species, that work as immunostimulants, anti-inflammatory, antimicrobial, and antioxidants for aquatic organisms (Tiwari et al. 2021).

Aquaculture wastewater treatment using microalgae

Water is one of the most important natural sources to survive on the planet, but diverse sources are contributing toward water contamination by discharging waste into the water bodies, which includes industrial, domestic, dairy, and agricultural waste (Amit and Ghosh, 2018). Wastewater contains organic (carbohydrates, fats, proteins, and amino acids) and inorganic pollutants (sodium, calcium, potassium, magnesium, chlorine, sulfur, phosphate, bicarbonate, ammonium salts, and heavy metals). This needs to be treated before discharging into water bodies (Tiwari and Marella 2019). A plethora of aquaculture pollutants can be remediated by the unique potential of microalgae as elaborated in Table 1. Commonly used microalgae for aquaculture wastewater treatment are belongs to *Ankistrodesmus*, *Chlamydomonas*, *Chlorella*, *Oscillatoria*, *Euglena*, and *Senedesmus* genera (Sirakov et al. 2015).

The management of water quality for aquaculture is highly significant for enhanced productivity as the pollutants or toxic contaminants in aquaculture can be accumulated in fish, crustaceans, mollusks, and bivalves, which can create serious problems in them and also for those who consume these aquatic organisms (Salces et al. 2019; Tiwari and Marella 2019). Apart from that one of the major issues is the overpopulation of fishes that can make the least genetic diversity in water bodies. This low genetic diversity can cause an imbalance of the ecosystem via leading the marine life extinction. Genetic diversity is required for long-standing evolution toward environmental changes. So, aquaculture promotes those species which are in demand

Table 1 Aquaculture wastewater remediation by microalgae

Aquaculture wastewater	Microalgae	Advantages	Nutrient removal	References
Aquaculture fishery wastewater	*Chlorella sorokiniana*, *Ankistrodesmus falcatus*, *Scenedesmus obliquus*	Nutrient removal of ammonia, nitrate and phosphate	NH_3-86.45–98.21% NO_2-75.76–80.85% P-98.52–100%	Ansari et al. (2017)
Fishery wastewater	*Synedra* sp.	Nutrient removal	NO_3–N-0.01–0.65 mg/L	Li et al. (2017)
Fish and shrimp in aquaculture	*Chlorella ellipsoidea*, *Scenedesmus dimorphus*	Improve fish breeding, survival rate and wastewater treatment	–	Kim et al. (2019)
Saline salmon aquaculture wastewater	*Chlorella minutissima*	Total nitrogen and phosphorus removal	N-88% P-99%	Paw et al. (2019)
Fishery wastewater (*Mugil cephalus*)	*Isochrysis galbana*, *Tetraselmis suecica and Dunaliella tertiolecta*	Dissolved inorganic nitrogen and phosphorus removal	N-90% P-79%	Andreotti et al. (2017)
Sea cucumber aquaculture wastewater	*Nitzschia* sp.	Total nitrogen, ammonium, nitrate, nitrate and total phosphate removal	TN-54.86% AN-95% NN-56.4% TP-16.80–27.6%	Xing et al. (2018)

for consumption without disturbing the natural environment (Healey et al. 2016).

The major source of contamination in aquaculture wastewater arises from wastes from fish (fish excreta) farming that contain nitrogen and phosphorous, which are harmful to the environment and can cause many serious problems like hypertrophication (Khatoon et al. 2016). Another reason for aquaculture water pollution is the accumulation of traditional feeds which are rich in nutrients mainly lipid and protein and later on, the leftover feed is slowly converted into a soluble form by bacterial activity, leading toward oxygen depletion in the water (Marella et al. 2020). In addition, exacerbated discharge of nitrate and phosphate facilitates the harmful algal blooms that cause oxygen depletion in the closed aqua ecosystem and can consume oxygen at the same time, producing some toxic elements, posing a serious problem for the health of aquatic life (Han et al. 2019).

The utilization of wastewater as nutrient by algae for biomass generation

Significant parameters to monitor and check the quality of water for fish farming, including dissolved oxygen, nutrient level, pH, and temperature (Ansari and Gupta 2019). Apart from that the level of chemical oxygen demand, solid waste, etc., need to treat. To treat wastewater, physical methods, chemical methods, or biological methods are used (Xing et al. 2018). To treat wastewater, eco-friendly and less cost-effective techniques are required. To resolve this problem, researchers are focusing to treat the wastewater by using the biological method by cultivating microalgae, which helps to reduce the excess of nutrients from the wastewater. Water remediation by using microalgae is an effective way because it can convert excess nutrient which is rich in nitrogen and phosphorous into useful biomass that contains lipid, protein, and carbohydrate (Amit and Ghosh, 2018). The algal cells use nitrogen for amino acid synthesis and supplemented cellular components. And phosphate is required to form a cell membrane by synthesizing components of DNA, RNA, ATP, and phospholipids (Xing et al. 2018). Thus, excess nutrients or waste nutrients can become food for microalgae which is useful to feed aqua animals, for human food, for fuel production, and for industrial purposes (Khatoon et al. 2016). The nutrient-rich microalgal biomass is used to feed fishes for their better growth. And have the potential to remediate approximately 70–90% of nitrate, sulfate, and phosphate from wastewater (Ansari and Gupta 2019), and effluent that is rich in oxygen is released after wastewater remediation by algae into water bodies (Xing et al. 2018) demonstrated that the sea cucumber, which is in demand owing to its nutritional value like good protein production and increase the nutritional value of the human diet, generates a huge amount of waste in aquaculture that rich in phosphorus and nitrogen. And to overcome these problems, microalgae *Nitzschia* sp. was used in aquaculture wastewater remediation. Many microalgae have been reported to efficiently remediate water which includes *Tetraselmis*, *Scendesmus*, and *Spirulina* (Amit and Ghosh, 2018).

System for wastewater treatment by cultivating microalgae

Microalgae can be cultured by using several techniques and the cultivation requires adequate light, temperature, pH, and less contaminated area. The algae can be grown in an open pond and closed pond systems (photobioreactors) (Tan et al. 2020). The treatment of aquaculture wastewater by using microalgae necessitates design of efficient algal productions systems and different cultivation systems have specific advantages and limitations. There are mainly three types of cultivation systems: open pond system, closed system (photobioreactors), and hybrid system (Tiwari and Marella 2019). For wastewater remediation, the open pond system has been used for large scale production of microalgae and there are two types of open pond systems, one is simple and cheap (non-stirred pond) and another is advanced (stirred pond). In the simple open pond, the natural light and air are used, while in an advanced open pond system there is the use of artificial air, light, and the nutrients are managed by stirring using a different form of ponds like high-rated algal pond which is advanced with paddle wheels and circular pond. The open pond system is cheap and easy to handle but the chances of contamination are high to cultivate axenic culture compared to a closed system (Tiwari and Marella 2019). Closed system (photobioreactors) which is enclosed in the inner environment where light, aeration, pH, and temperature all are provided artificially and can be controlled easily. In a closed system, there are various types of photobioreactors such as vertical, horizontal, airlift, tubular, and flat plate photobioreactors. A Closed system is more convenient and efficient than an open system because in closed system the chances of contamination are very less, but it is expensive than open system. The third system is known as hybrid or advanced pond system, as the name suggested it features an amalgamation of both of the systems, i.e., open system and closed system. In this type of system, microalgal cultivation was done firstly in an open system and then transfers in a closed system (Tiwari and Marella 2019).

Microalgae are fast-growing organisms that can grow in terrestrial and aquatic environment. To culture, the microalgae, the environment where they grow or survive (water) should be rich in nitrate, phosphate, vitamins, and trace element (major nutrients are phosphorus and nitrogen) but in the case of diatoms, including all the nutrients, one major component, i.e., silica, also required for their growth (Marella et al. 2020). Microalgae can reproduce fast in a liquid medium and their biomass production can improve by changing the culture conditions as in *Chlorella*, if nitrogen content is deficient then their biomass rich in lipids by 85% (Guedes et al. 2015). Apart to grow microalgae in different types of wastewater, they can also be grown in the number of media according to their requirement for their optimum growth. The required media for all algal or microalgal species is different, based on their nutrient requirement (micronutrients and macronutrients) such as diatoms required silica-rich media because their cell wall made up of silica. Microalgae can be grown in diverse wastewater such as domestic wastewater, industrial wastewater, palm oil milling effluents, or sewage wastewater and aquaculture wastewater (Tan et al. 2020).

Microalgae as biocontrol agents

The aquaculture industry is the fastest growing industry and a report suggested that in 2014, world aquaculture production earned approximately 160 billion from finfish, mollusks, and other aquatic animals but the occurrence of infection from bacteria, viruses, and fungus is a major challenge. Examples of infectious diseases in shrimps from viral pathogens are the White Spot Syndrome Diseases (WSSD), Yellow Head Disease (YHD) and the bacterial infection in shrimps is Early Mortality Syndrome (EMS) (Charoonnart et al. 2018). The microalgal compounds have antimicrobial potential and these compounds can be produced by microalgae under proper cultivation conditions such as intensity of light, pH, temperature, and specific culture media (Bhattacharjya et al. 2020, 2021). The metabolites like flavonoids, carbohydrates, and terpenes extracted from *Chlorella vulgaris* are known to be responsible to inhibit the growth of bacteria (Dineshkumar et al. 2017). Table 2 highlights the antimicrobial potential of microalgae.

Table 2 Antimicrobial activity by microalgae against targeted bacteria

Microalgae	Targeted pathogens	References
Chlorella minutissima, *Tetraselmis chui*, *Nannochloropsis* sp., *Arthrospira platensis*, and *Isochrysis* sp.	*Vibrio parahaemolyticus*, *V. anguillarum*, *V. splendidus*, *V. scophthalmi*, *V. alginolyticus*, and *V. lentus*	Kokou et al. (2012)
Nitzschia laevis, *Nitzschia frustulum*, *Navicula incerta*, *e Navicula biskanterae*, and *Navicula cf. incerta*	*Vibrio alginolyticus*, *V. campbellii*, and *V. harveyi*	Cardenas and Saavedra (2017)
Amphora sp.	*Bacillus cereus*, *Bacillus subtilis*, *Micrococcus luteus*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, and *Almonella enterica*	Boukhris et al. (2017)
Synechococcus elongatus, *Synechocystis* sp., *Amphiprora paludosa*, *Porphyridium cruentum*, *Chaetoceros muelleri*, and *Dunaliella tertiolecta*	*Bacillus subtilis*, *Staphylococcus aureus*, and *Micrococcus luteus*	Saavedra et al. (2010)
Anabaena variabilis	*Rhizopus stolonifer* and *Aspergillus niger*	Tiwari and Sharma (2013a)
Synechococus elongates and *Anabaena variables*	*Klebsiella* sp., *Enterococcus* sp., and *E. coli*	Tiwari and Sharma (2013b)

Bacterial disease and its treatment by microalgae

Bacterial pathogens are considered the main cause of infection in fishes and the most usual bacterial pathogen species belong to *Aeromonas*, *Pseudomonas*, and *Vibrio* genus (Charoonnart et al. 2018). Bacterial pathogens can cause serious mass mortality in aquaculture, by infecting the aquaculture organisms, for example, bacterial infection in finfish is mainly caused by *Aeromonas* sp. and *Pseudomonas* sp., that induce hemorrhages while *Vibrio* sp. triggers vibriosis in marine fish. Many species of *Vibrio* can spread disease and can be involved in massive mortalities in bivalves and shrimps. To control bacterial diseases, antibiotics are used to save aquatic organisms, but bacteria have developed antibiotic resistance against existing antibiotics and there are several side effects of synthetic antibiotics. Envisaging a natural resource to combat the myriad of bacterial infections is the need of the hour and the antibacterial efficacy of microalgae holds immense potentials (Dineshkumar et al. 2017).

Microalgae are available all around the world and they are consumed and exposed to disease-causing microbes such as bacteria, fungi, and viruses. So, to protect themselves from the pathogens they need to develop a defense mechanism against these pathogens. Several studies elucidated that microalgae or algae possess antioxidant, anti-inflammatory, and antimicrobial properties (Tiwari et al. 2021). The microalgae or algae which live in an environment where the bacterial population is dense can synthesize the antibacterial metabolites to kill the bacteria than those who live in a bacteria-free environment. The antimicrobial property of microalgae is depending on the species, their culture condition, and their growth conditions. The *Vibrio* species are the target pathogen to test the antibacterial effects of microalgae. Microalgae *Tetraselmis suecia* exhibits antibacterial effect against *Vibrio alginolyticus*, *Vibrio anguillarum*, *Vibrio parahaemolyticus*, and *Vibrio vulnificus* (Kokou et al. 2012).

The antibacterial compounds in microalgae include a wide range of metabolites like long-chain polyunsaturated fatty acids (LC-PUFA), for example, eicosapentaenoic acid (EPA), sterol which is active against gram-positive and gram-negative bacteria. So, when aquatic animals eat microalgae, then the chances of the infection get reduced. Fatty acid from diatom *Phaeodactylum tricornutum* was found to have antibacterial activity against Methicillin-resistant *Staphylococcus aureus* (MRSA), for that three unsaturated fatty acids are found to involve in antibacterial activity. The three unsaturated fatty acids are:

1. Eicosatetraenoic acid (EPA)
2. Palmitoleic acid (PA)
3. Hexadecatrienoic acid (HTA)

It was predicted that the cellular membrane of bacteria was first targeted to kill it. Fatty acids damage the bacterial cell membrane; resulting in cell leakage and cellular respiration get reduced (Falaise et al. 2016). Phenolic compounds are secondary metabolites that have antimicrobial activity by changing the cell permeability and damaging the macromolecules of microbes (Perez et al. 2016).

The microalgal pigment, i.e., C-phycoerythrin, C-phycocyanin, and Fucoxanthin, also contributes toward imparting antimicrobial potential. It was reported that pigments from *Spirulina platensis*, *Anabaena variabilis*, *Synechococcus elongates*, *Skeletonema* sp., *Chaetoceros* sp., and *Thalassiosira* sp., demonstrated good antibacterial activity against *Escherichia coli* and *Staphylococcus*

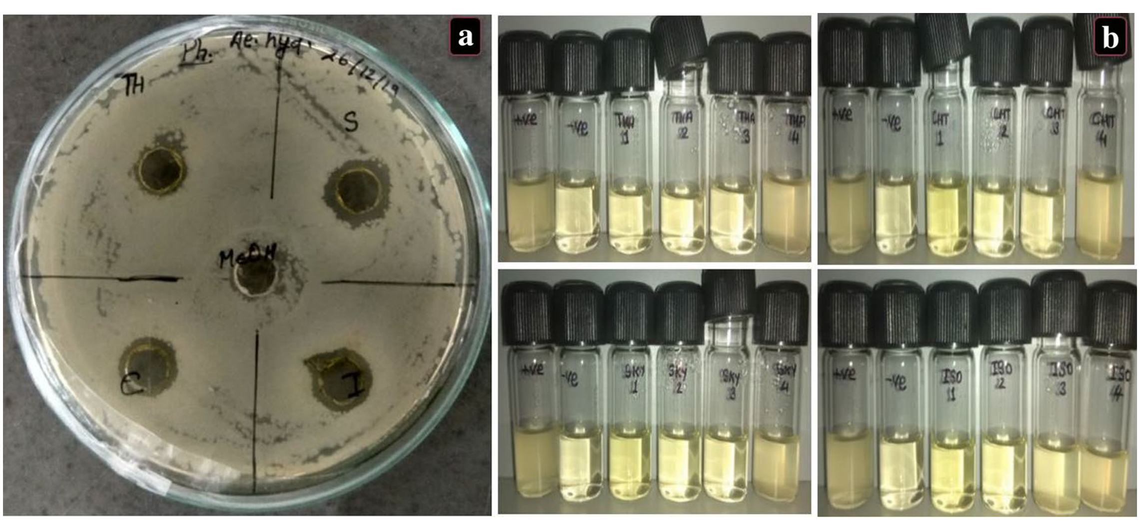

Fig. 2 Inhibitory effect of microalgal extract (*Thalassiosira* sp., *Skeletonema* sp., *Chaetoceros* sp., and *Isocrysis* sp.) against fish pathogen *Aeromonas*, **a** zone of inhibition, and **b** minimum inhibition concentration (Bhattacharjya et al. 2020)

aureus (Mishra and Tiwari 2021). Antibacterial activity was tested against fish pathogen *Aeromonas* by using diatom species *Skeletonema*, *Thalassiosira*, and *Chaetoceros* where it showed growth inhibition of bacteria (Fig. 2). A clear zone of inhibition was observed and diatom *Thalassiosira* inhibited the maximum growth of *Aeromonas* (Bhattacharjya et al. 2020).

Viral disease

Diseases in fish are also caused by viral pathogens, and the reports suggested that the disease in fish caused by viruses includes betanodavirus like nervous necrosis virus (NNV), Megalocytivirus such as infectious spleen and kidney necrosis virus (ISKNV), and red sea bream iridovirus (RSIV) (Charoonnart et al. 2018).

Treatment by antibiotics only targets the bacterial infection it does not protect against viral infection. So, to overcome this problem vaccines are developed which is efficient against bacterial pathogens as well as viral pathogens but there is also a challenge to inject the vaccine into the intramuscular which can hurt the fishes and aquaculture animals. This vaccine needs to store at a cold temperature which is very expensive. So instead of injecting the vaccine, there was the finding of another method that is direct spray the vaccine but drawback of this method is, the need of excess amount of vaccine and it can become a stressful situation for the fish (Charoonnart et al. 2018). So, in this context, the algae are found to be more efficient against viral diseases such as antiviral property from *Gelidium cartilagineum* algae exhibited protection from influenza B and mumps viruses to embryonated eggs. The compound from Cyanobacteria is considered a better source of antiviral infection. A compound sulfated polysaccharide from cyanobacteria is considered to have antiviral efficacy against human immunodeficiency virus type 1 (HIV-1) and herpes simplex virus type 1 (HSV-1).

Previous studies showed that many antibiotic compounds have been isolated from the cyanobacterial and microalgal extracts, which validates that the cyanobacteria have antiviral and antineoplastic compounds (Falaise et al. 2016). Terpenes are one of the bioactive compounds that are produced by algae. Terpenes such as diterpene neophytadiene, sesquiterpene cartilagineum, obtusol, and elatol isolated from seaweed have the antiviral property (Perez et al. 2016). The antiviral compounds from the microalgae *Dunaliella salina* and *Haematococcus pluvialis* were extracted by using the pressurized liquid extraction (PLE) technique where water, ethanol, and hexane solvent were used to evaluate antiviral activity against herpes simplex virus type 1 (HSV-1) and found that the ethanolic extract of *H. pluvialis* inhibits the maximum (85%) of viral infection, whereas the aqueous and hexane solution inhibits the minimum growth, i.e., 75% and 50%, while both ethanolic and aqueous extract of *Dunaliella salina* only inhibits (65%) of viral infection (Santoyo et al. 2012).

Antifungal activity

Apart from bacterial and viral disease, fungal disease in fish is a major concern. A few examples of fungi that caused disease in fishes are *Aspergillus terreus*, *Aspergillus clavatus*; *Alternaria* spp, *Saprolegnia parasitic*, *Saprolegnial apponica*, *Saprolegnia ferax*, and *Saprolegnia hypogyna*. The increasing problem of fungal infections prompted the search for newer and safer agents to fight against fungal infections in fishes (Patel et al. 2018). Instead of chemical treatment, microalgae are found to be the best way to treat fungal infection. Cyanobacteria were found to have antifungal properties against fungal strains: *Aspergillus niger*, *Aspergillus fumigates*, *Trichophyton rubrum*, and *Macrophomina* sp. Cyanobacteria produce intracellular and extracellular metabolites that have antibacterial, antifungal, antiviral, and anticancer potential (Tiwari and Sharma 2013a, b).

Reported that pigment from *Haslea karadagensis* has antifungal activity against marine fungi: *Lulworthia* sp., *Dendryphiella salina*, and *Corollospora maritima*. Also showed antibacterial and antiviral activity against *Pseudoalteromonas elyakowii*, *Vibrio aestuarianus*, *Polaribacter irgensii*, and *Herpes simplex virus* type 1 (HSV-1), respectively (Gastineau et al. 2012). Ghanayem tested the antimicrobial activity of *Spirulina platensis* extract against fungi and bacteria where the methanolic extract of *Spirulina platensis* of the concentration 150 mg/mL was found to be effective against *Candida* sp. The maximum inhibition was found against *Candida tropicalis*, while the least inhibition effect was shown in *Candida parapsilosis* (Ghanayem 2017).

Suitability of algal biomass for aquafeed

Fishmeal is the source of aquaculture feed that is rich in protein, fatty acids, vitamins, and minerals. Fishmeal is the brown flour that is procured from the whole fish by cooking, drying, and pressing it. But fishmeal is limited and cost-effective that can rise up to 30 to 60%. So, these problems need to be solved and need to find out a new source of nutritious fish food. Production of algae is the best source and inexpensive source for aquafeed and better replacement of fishmeal that can save about 40% of feeding cost than fishmeal which cost is known two-third of total aquaculture costs (Bhattacharjya et al. 2021). Algae or microalgae are important for aquatic life because they are eaten by zooplankton and are vital in the aquaculture food chain. The use of algae is considered as the main ingredient for fish in aquafeed and it has been reported that a very few amounts of algae are sufficient for the fish diet that gives better growth rate, feed utilization efficiency, intestinal microbiota, physiological activity, give strength to fight against diseases, and capacity to hold the protein in the winter season to decrease the chance of feed intake and control the stress response. The nutritional value of microalgae depends on various factors that are cell size and shape, digestibility, biochemical contents, and animal feeding requirements of microalgae (Guedes et al. 2015). Microalgae are considered a rich source of nutrition as a report by Alberto reports that microalgae are the source of carbohydrate, protein, lipid, and dietary fiber (Niccolai et al. 2019). It is reported that microalgae have 30–40% protein, 10–20% lipids, and 5–15% carbohydrate in the late log phase (Shah et al. 2018). The nutritional value of microalgae is varying from species to species; some may be rich in carbohydrates while some of them are rich in protein, vitamins, or lipids. Table 3 elaborates the aquafeed potential of microalgae.

Among the other microalgae, *Spirulina* is used as fish feed which is known to have better growth. It has been predicted that the demand for fish production will be increased day by day so that algae or microalgae will be high on demand for fish food; thus, it will provide a great amount to the algal and aquaculture industry. And for that high production of the bioactive compound is required that can get from selective strain or by genetic modification while some of the chemicals as metabolites can modulate the cellular metabolism that can activate the high yield production of bioactive compounds, for an example, epigallocatechin gallate and cyclin-dependent kinase 2 inhibitors can trigger the production of intracellular lipids in *Nannocloropsis* and *Phaeodactylum tricornutum* (Talero et al.2015).

Protein is the major metabolite of microalgal biomass, and its productivity depends on several factors such as different species, culture conditions (temperature, pH, and light) and nutritional value, and environmental factors. Nitrogen plays an important role in increasing the yield of protein. Reported that the microalgae show higher protein yield when it has grown in high nitrogen concentration (Ansari and Gupta 2019). In ideal fishmeal, high protein content including all required amino acids is strongly recommended, and usually, in the fish meal, plant (crop) protein is used, in which few essential amino acids are not present. In fish meal, adequate amount of amino acid (lysine, methionine, etc.) is required, so, microalgae have been found to have all essential amino acids (Chrapusta et al. 2017). And these amino acid varying from species to species like marine algae has fewer sulfur-containing amino acids than freshwater microalgae (Ansari and Gupta 2019). Microalgae like *S. platensis* and *C. vulgaris* can produce a high amount of protein content and this quality makes them a good source of food for aquatic life (Bhattacharjya et al. 2021).

The carbohydrate content is less required than protein and lipids, but it is known as the main substrate for various biofuel productions such as bioethanol and biohydrogen (Singh et al. 2021). Photosynthetic microalgae convert solar energy into chemical energy via several complex reactions called photosynthesis. This photosynthetic reaction is completed into light and dark reactions. In the light reaction, chlorophyll pigment captures the solar energy and used to break the water molecules into an electron, proton, and oxygen, and then, this proton and electron produce energy transporter, i.e., NADPH and ATP, while in dark reaction, the NADPH and ATP are used to reduce carbon dioxide to carbohydrate via Calvin cycle. Carbohydrate production in algae fulfill two requirements: first in cell wall as a structural component and second for storage purpose in cell. As the storage component, carbohydrate gives the required energy during metabolism. The storage compounds (carbohydrates and protein) in algae help in growth adjustment when the environmental conditions change (Bhattacharjya et al. 2021). The carbohydrate is species specific such as cyanobacteria synthesize glycogen, red algae synthesize floridean starch, and green algae synthesize amylopectin-like polysaccharides

Table 3 Microalgae as feed for aquaculture organism

Microalgae	Advantages of microalgae as feed	References
Chaetoceros calcitrans, *Nannochloris maculate*, and *Tetraselmis chuii*	Protein and lipid content were higher in *N. maculate* and *T. chuii* beneficial as live feed utilization for aquaculture	Khatoon et al. (2016)
A. platensis, *P. tricornutum*	Protein content was estimated 63.9 ± 1, 38.8 ± 0.11 and carbohydrate content 12.8 ± 0.21, 11.0 ± 0.70 (% of algal powder)	Niccolai et al. (2019)
Coccomyxa onubensis	Protein, lipid, carbohydrate and dietary fiber content was found 44.6%, 5.4%, 24.8%, and 15.73%, respectively protein (44.60%), dietary fiber (15.73%), carbohydrate content (24.8%), and lipid content (5.4%)	Navarro et al. (2016)
Asterarcys quadricellulare sp.	20.0 ± 0.3% of lipid and 36.6 ± 2.0% of carbohydrate content found in *A. quadricellulare*	Oliveira et al. (2017)
Chlorella vulgaris	*C. vulgaris* is used to feed catfish *Clarias gariepinus* having lipid 24.40 ± 0.09 carbohydrate 12.09 ± 3.17 and protein 54.65 ± 0.07	Enyidi (2017)

(starch) (Markou et al. 2012). Microalgal polysaccharides can adjust the immune system and inflammatory reactions, so, this quality makes them a more attractive source as biologically active molecules, for example, used in cosmetics, as natural curative agents, and used in food products (Tiwari et al. 2021).

Microalgae are also rich in vitamins and minerals that are necessary organic micronutrients. Vitamins cannot be directly synthesized in enough amounts only they can be obtained from the diet. In microalgae, vitamin production depends on the presence of nitrogen. At a low concentration of nitrogen, cyanobacteria produce the least vitamin B 12. So, the concentration of nitrogen in the culture medium affects the content of vitamins. For aquaculture animals, vitamin riboflavin is important that is found in microalgae (Chew et al. 2017). *Chlorella* and *Spirulina* species (beta carotene and B 12) have more vitamins than plants and animals. Most of the microalgae contain an active form of vitamin E, i.e., α-/β-tocotrienol or α-/β-tocopherol (vitamin E) at a very high concentration that has antioxidant properties for example, *Tetraselmis suecica* and *D. tertiolecta* produce high vitamin E under the less nitrogen condition (Guedes et al. 2015; Sathasivam et al. 2019). And vitamin E is also used to treat heart and eye disorders, Alzheimer's disease, and cancer. Vitamin C is stored by a few algal species that have antioxidant activity, essential for the synthesis of neurotransmitter, prevents cancer and atherosclerosis. Algal species *Dunaliella* and *Chlorella* contain high Vitamin C content (Sathasivam et al. 2019). The algae have the potential to replace inorganic salt with vitamins and minerals.

Microalgae are highly exposed to oxygen and radical stress due to their phototrophic nature. They produce valuable bioactive compounds that have various important roles like protecting against oxidative and radical stressors (Tiwari et al 2021). Pigments are one of the important bioactive compounds that have a number of applications like antibacterial and antioxidant activities.

Phycocyanin pigment secreted by *Spirulina* helps to treat damaged bone marrow stem cell by controlling the production of White blood cell (WBC). The astaxanthin which is a keto-carotenoid synthesized from microalgae is reported to be essential for the survival and growth of shrimps, salmon, and trout (Nguyen 2013). Astaxanthin protects the algae from UV radiation and photooxidation of polyunsaturated astaxanthin. Nguyen (2013) reported that the algae which synthesized astaxanthin are *Haematococcus pluvialis*, *Chlorella zofingiensis*, and *Chlorococcum* sp., the red yeast *Phaffia rhodozyma* (Nguyen 2013). Carotenoids are a class of natural fat-soluble pigments found principally in algae where they play a critical role in the photosynthetic process. In human beings, carotenoids can serve several important functions. The most widely studied and well-understood nutritional role of carotenoids is their provitamin A activity. Carotenoids are found to be powerful antioxidants. Beta-carotene is an essential carotenoid as it is the form of provitamin A and is used in many food products. β-carotene is a natural pigment derived from green algae, is used as a yellow–orange food coloring agent, and help to prevent certain types of cancers (Tiwari et al. 2021). Few species of *Dunaliella* produce beta-carotene at a very high amount under extreme temperature, high light intensity, and high salinity and have anti-cancerous and antioxidants property. For the production of beta carotene, proper environmental conditions are required. There are cis and trans isomers of beta carotene, where the cis isomer of beta carotene has an effective role as it protects the cell from oxidative damage (Sathasivam et al. 2019). The algal pigments are great reservoirs of highly valuable applications and need extensive investigations further.

The Omega-3 fatty acid is one of the most important fatty acids that have health benefits on aquaculture organisms as well as on human beings as it has anti-inflammatory, anti-blood clotting property and helps in regulating blood pressure and diabetes. Algae are known as the novel source of omega-3 fatty acids where the growth phases of algae play an important role in the production of different types of fatty acids (Tiwari et al. 2021). It is reported that at the logarithmic phase, phospholipids are high in microalgae while at the stationary phase they are rich in triacylglycerols. Eicosapentaenoic acid (EPA), arachidonic acid (AA), docosahexaenoic acid (DHA), and α-linoleic acid (ALA) are reported to play an essential role in larval growth. Omega-3 fatty acid or polyunsaturated omega-3 fatty acid (PUFA) is secreted by microalgae at a very high amount (Han et al. 2019). PUFA regulates the membrane fluidity, electron or oxygen transport, and thermal adaptation of cellular and tissue metabolism (Tiwari et al. 2021). It is known that different species are rich in a different amount of omega-3 fatty acid or polyunsaturated omega-3 fatty acid (PUFA) like docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) such as *Bacillariophyceae* and *Chrysophyceae*, class of algae, are rich in EPA and DHA (Tiwari et al. 2021) while more amount of DHA is found in *Dinophyceae*, *Prymnesiophyceae*, and *Euglenophyceae*, whereas EPA is found at a very high amount in *Cryptophyceae*, *Prasinophyceae*, *Rhodophyceae*, *Xanthophyceae*, and *Glaucophyceae* (Shah et al. 2018). More extensive investigations are in progress worldwide for elucidating more vivid applications of microalgae triggering their aquaculture wastewater remediation, biocontrol, and aquafeed potential for the development of a completely circular system with minimal waste and maximum utilization of available sustainable resources.

Conclusions

The progress of the aquaculture industry is greatly influenced by significant challenges like the accessibility of resources that are natural in origin and the environmental impact. The sustainable utilization of resources, high productivity, and good profit can accelerate this industry and help in achieving the SDG targets wherein the objectives can help in eradication of poverty (SDG 1), providing adequate nutrition (SDG 2), and aid in substantial growth (SDG 8) for a better tomorrow. In this regard, the utilization of microalgae is a promising option owing to their unique metabolic potential and their robustness to grow in diverse types of aquaculture waters. The aquaculture wastewater is rich in nitrate and phosphate and can trigger eutrophication when discharged and growing algae is magnificent, which efficiently manages the consumption of excess nitrate and phosphate as a source of their nutrition. The algal biomass is rich in proteins, carbohydrates, fatty acids, and other useful metabolites which promote fish health and are easily digestible even by the larvae, which do not readily ingest artificial aquafeeds. The antimicrobial potential of microalgae is yet another important feature that can act as natural biocontrol agents in aquaculture against a myriad of fish pathogens. Through this circular bioeconomy approach, it is evident that microalgae can play a lead role in the improvisation of feed quality and enhanced feed utilization promoting better fish health concomitant with the utilization of minimal eco-friendly resources.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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