




# Algae-Based Biorefinery as a Sustainable Renewable Resource

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Received: 15 March 2021 / Accepted: 28 June 2021 / Published online: 20 July 2021  
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## Abstract

Algae are a large and diverse group of autotrophic organisms that are multicellular and single-celled and found in a variety of environments. Biofuel production and value-added chemicals produced through a sustainable process are represented by the biorefinery of algae. Algae are important because of the production of polysaccharides, lipids, pigments, proteins, and other compounds for pharmaceutical and nutritional applications. They can also be used as raw materials for biofuel production. Moreover, they are useful for wastewater treatment. All these factors have absorbed the attentions of researchers around the world. This review focuses specifically on the potentials, properties, and applications of algae as a sustainable renewable resource, which can be a good alternative to other sources due to their high biomass production, less land required for cultivation, and the production of valuable metabolites.

**Keywords** Algae · Biorefinery · Metabolites · Biofuel

## Introduction

Algae are photosynthetic organisms that grow in a wide range of habitats, including lakes, rivers, oceans, and even sewage. They can tolerate a wide range of temperatures, salinity and pH values and can grow alone or in coexistence with other organisms [1]. Algae are generally classified as Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green

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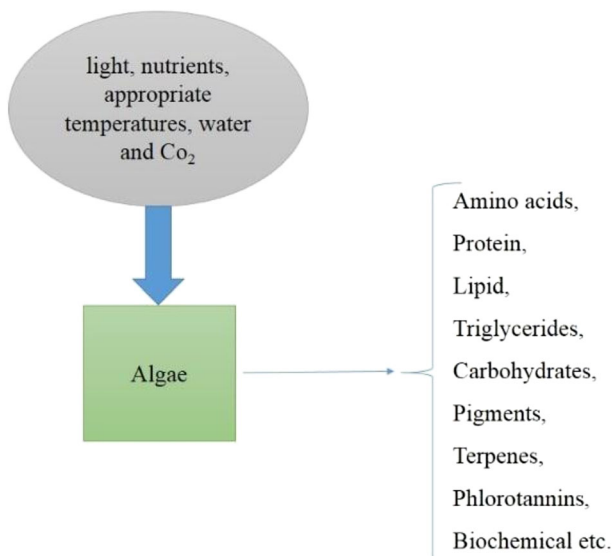
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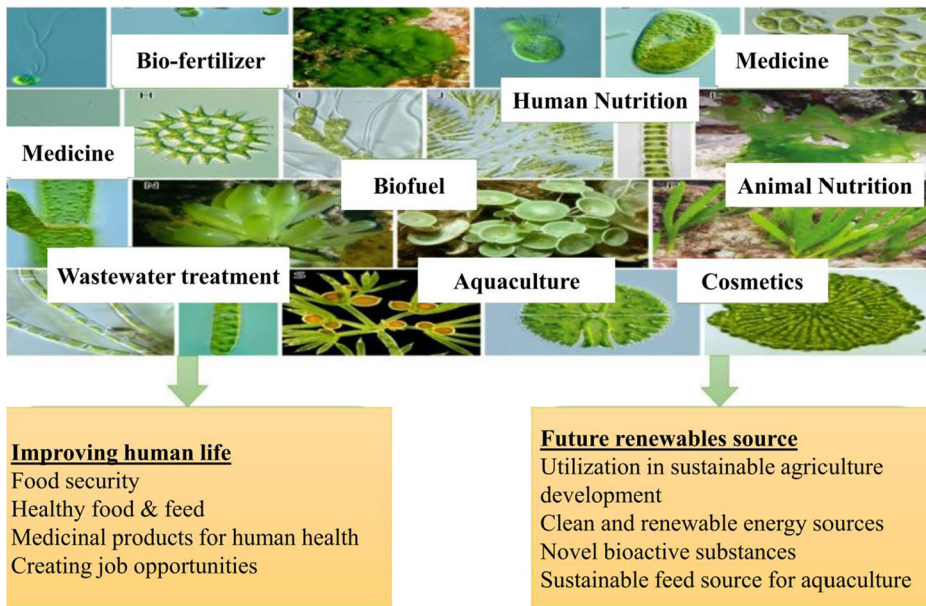
algae). Algae have different life cycles and have two genetic layouts: monogenetic and digenetic. They range in size from the microscopic species *Micromonas* to brown algae up to 60 m long. Thus, they are generally classified into two groups: macroalgae (seaweed) and microalgae (unicellular) [2]. Algae are eukaryotic (nucleated) photosynthetic organisms that can convert  $\text{CO}_2$  and water into  $\text{O}_2$  and macromolecular organic matter (carbohydrates and lipids) and are therefore a source of carbon and energy to other organisms. They are one of the primary producers. They can be divided broadly into macroalgae and microalgae [3, 4].

Algae photosynthetic pigments are more diverse than plants, so they are more efficient than plants in photosynthesis (Figure 1). Algae have a variety of habitats, snow and polar glaciers, hot springs, soil, rocks, other organisms growing on animals such as turtles and sloth, growing on fungi, terrestrial or other algae, and tree bark [5].

Algae are important because of the production of polysaccharides, lipids, pigments, proteins, and other compounds [6]. Algae and microalgae are cultivated for food production, production of useful compounds, biorefinery, cosmetics, aquaculture, biofuels, etc. (Figure 2). They need light, nutrients, appropriate temperatures, and  $\text{CO}_2$  to grow [7]. Most algae coexist with several microorganisms throughout their lives [8]. Bacteria play an important role in stimulating algae growth, spore germination, and morphogenesis. There are extensive interactions between algae and bacteria. Microalgae produce  $\text{O}_2$ , which can be used by bacteria for respiration, and bacteria produce  $\text{CO}_2$  for algae consumption [9]. They can convert micronutrients and macronutrients (iron carriers, growth stimulants, and antibiotics) into forms that can be used by microalgae [10] as well as bacteria. They secrete vitamins and some effective cofactors that are necessary for the growth of some microalgae [11]. And of course, as mentioned, they can also have negative interactions with each other. Fungi, bacteria, viruses, and parasites can infect microalgae culture, or other types of algae can enter the system and compete with the main algae [12]. Bacterial and viral pathogens can weaken or break down the algal cell wall, which is an important step in extracting algae-based chemicals [13]. In addition, microorganisms that coexist with algae can help host to cope with changing conditions [14].



**Figure 1** The nutritional value produced by algae



**Figure 2** Applications of algae in a biorefinery

Industrial biotechnology, also known as white biotechnology, uses enzymes and microorganisms to make bio-based products including chemicals, pharmaceuticals, plastics, food ingredients, textiles, and biofuels. Algae harvest and biorefinery is a part of industrial biotechnology. Bio-based products including chemicals, pharmaceuticals, plastics, food ingredients, textiles and biofuels can be produced through industrial biotechnology [15]. Technical and economic analysis is carried out to determine the economic efficiency of the processing technologies at the research and development stage. Algae and microalgae have a high capacity to absorb carbon dioxide. Their cultivation in open systems is less efficient than in closed systems. Conditions should be adjusted to increase biomass productivity, thereby reducing carbon dioxide uptake and reducing the area needed for cultivation, and biomass-related operating costs would be reduced [16].

Algae and microalgae cultivation systems are divided into two categories: open cultivation system and closed cultivation system. Open cultivation system has low production and implementation costs, but the disadvantages of open cultivation are lack of control over environmental conditions and the possibility of high pollution. Closed culture systems are recommended if the quality of the final product is to be considered. Closed culture systems are usually used to achieve maximum microalgae growth. In this system, growth indices such as temperature are better controlled and the amount of pollution is less than the open system, but they are not completely safe. They have a high surface-to-volume ratio that increases system efficiency. Evaporation is low so water is not wasted [17, 18].

Today, much of the revenue from marine biotechnology is devoted to algae. That is why they have received a lot of attentions from economists. Algae do not compete with food crops and have higher energy yields than food crops. On the other hand, photosynthesis is 5 to three times faster than plants. This has made these organisms a viable choice for biotechnological production [19].

Investigating the financial and technological aspects of algae production shows that they can be used in various aspects of material production.

## Algae as Food and Feed

Humans and animals need the source of nitrogen and essential amino acids to make their structural and functional proteins, such as enzymes and protein hormones, which are provided through the consumption of proteins. The use of algae to feed humans dates back to the ancient times. Macroalgae and some microalgae are cultivated for foods, feed, and food additives [20].

Proteins, vitamins, and polyunsaturated fatty acids are the major valuable nutrition of algae and microalgae. There are several ways to improve the content of monounsaturated fatty acids in microalgae: manipulating conditions such as light intensity, nutrient status, and temperature [21]. Algae and microalgae produced for humans and animals usually have a high protein content (70–60% for example), as well as a rich source of fats (with particular emphasis on omega-3 fatty acids and carotenoids); polysaccharides; minerals; vitamins A, B, C, and E; enzymes; hormones; and pigments [22].

Algae, fungi, and bacteria can be used to produce single cell proteins. These microorganisms have high proliferative potential, resulting in a high protein content of about 30 to 80% of the dry weight of the mass [23]. For example, up to 70% of the dry weight of the *Spirulina platensis* is protein [24].

Daily protein intake is very important. Lack of protein causes many problems for the human body, such as fatty liver, muscle weakness and bone fractures, infections and problems with the health of nails and human hair, and poor growth in children. Some evidence suggests that consuming too little protein can increase appetite and lead to obesity. Due to the growing population of the world, it is estimated that the demand for meat will reach 400 million tons by 2050 and dairy products by 800 million tons [25]. However, plant protein is relatively inefficient to become meat and as 6 kg of plant protein is needed to produce 1 kg of meat protein. This indicates a mismatch between increasing meat production rates and increasing population [26]. In addition, *Arthrospira platensis* and *Chlorella vulgaris* are also marketed as functional foods due to their high vitamin and mineral content. They are generally recognized as safe by the European food safety authority [27].

Agar is extracted from the red seaweed such as *Gracilaria*, which is used in the food industry and in the culture medium in laboratories. Carrageenans, which are also extracted from species of red seaweeds such as *Chondrus* and *Gymnogongrus*, provide gel qualities [28].

The use of algae in animal nutrition provides protein, amino acids, fats, biologically active substances, and so on. Moreover, it has effects such as improving the immune system, metabolism of fats, antiviral and antibacterial phalates in the intestine, and resistance to stress [29, 30]. It is not commercially viable due to the high algal biomass requirement for animal feed. That is why the algal biomass/extracts are not considered an essential feed source; however, they can be considered food quality enhancers [31].

## Use of Algae in Medicine

Alga has always been of interest in the production of antibiotics and important active compounds. Various products are derived from algae such as antivirals [32], antimicrobials [33], antifungal [34], anticancer [35], and many more.

The widespread resistance to antibiotics in the world, such as  $\beta$ -lactams and quinolones, has made research on natural antimicrobial drugs important for accessing new pharmaceutical sources. Numerous studies have shown that algae extract has antifungal, antibacterial, and antiviral properties [36]. Antimicrobials extracted from seaweed can be used to enhance food safety and quality [37]. Antibacterial activity of algae depends on factors such as their season of collection, environment, and different stages of algae growth [38]. Chemical studies on algae have shown compounds such as phenol (antioxidant properties), tannin (bind and precipitate proteins), saponin (varied biological activities), flavin (light receptors), and steroids (membrane functioning and hormone signaling) [39, 40].

Although vitamins, polyphenols, and phycobiliproteins are not found in algae, water soluble antioxidants are found in them. Antioxidants play a key role in the later stages of cancer. Humans are interested in species such as *Chondrus crispus*, *Himantalia elongate*, and *Undaria pinnatifida* because of their low calorie content, and their high content of minerals, vitamins, and fibers [41]. The ethanolic extract of *Dunaliella salina* was evaluated on the A549 human lung cancer cells. The results showed that the ethanol extract of *Dunaliella salina* can exert anti-proliferative effects and stimulate the cell cycle arrest of G0/G1 and apoptosis of A549 lung cancer cells [42].

As biochemical diversity of algae is high, they are considered a rich source of biopharmaceuticals. Their market value appraised for \$2500 to \$5800 a thousand per ton. The main group of pharmaceutical compounds of algae includes polysaccharides, pigments, terpenoids, alkaloids, phenolic compounds, fatty acids, and peptides [43]. For example, polysaccharides have anti-inflammatory activity, as they bind to the surface of white blood cells and interrupt their transportation [44]. For instance, the activity of fucoidan derived from *U. pinnatifida* was examined on kinds of prostate cancer cells. Apoptosis was induced and p38MAPK pathways were inactivated by extracted polysaccharide [45].

Carotenoids, one of the most abundant group of molecules in algae, include different groups such as fucoxanthin, astaxanthin, and zeaxanthin [46]. Carotenoids, for example, fucoxanthin, inhibit cyclin-dependent kinase in the treatment of melanoma cells [32]. Also, the peptides isolated from *S. platensis* have anti-tumor effect against human liver cancer MCF-7 and HepG2 cells [47]. Studies have shown that some antioxidants, such as beta-carotene, can be useful in oral cancer [48]. Therefore, commercial use of algae as food and medicine should include all aspects including nutritional value, access to bio-products, and its toxicity and subsequent biological activities to achieve a useful and desirable product [28].

Coronavirus (SARS-CoV-2) is a zoonotic virus and the cause of COVID-19 infectious pneumonia, which was declared a global epidemic by the World Health Organization (WHO) on January 30, 2020 [49]. Studies over several decades have shown that polysaccharides have antiviral properties [50]. As mentioned, algae are rich in biologically active compounds, so they are pharmacologically active and have antiviral properties [51]. Algae are a rich source of various types of polysaccharides. The red algae *Porphyridium* sp. has been reported to contain sulfated polysaccharides that can be used to fight the coronavirus. These compounds are used as coatings to protect against the coronavirus on the sanitary items [52]. Microalgae are a source of large amounts of omega-3 PUFA [53]. Omega-3 PUFA is used as an adjunct therapy to treat cardiovascular complications caused by coronary heart disease [54].

## Use of Algae as Fertilizer

The most important goal of sustainable agriculture is to maintain the balance of the agricultural ecosystem alongside crop production. Sustainable agriculture must be ecologically sound, economically justified, and socially desirable. The use of fertilizers, whether natural or chemical ones, provides nutrients to the soil and increase plant growth and yield [55]. Nowadays, the use of chemical fertilizers as the fastest way to compensate for the deficiency of soil nutrients has been greatly expanded. Excessive use of chemical fertilizers causes irreparable damage to the environment and human health. For example, nitrogen fertilizers cause contamination of water and soil resources, and eventually result in numerous diseases in humans and other organisms [56].

The production of biofertilizers from microorganisms such as bacteria, algae, and fungi can be a good alternative to chemical fertilizers by their interactions in rhizosphere, benefiting crop plants by the uptake of nutrients (Table 1). To reduce these risks, resources and inputs should be utilized which, in addition to meet the plant's nutritional needs, will lead to the sustainability of long-term agricultural systems [57].

Algae are divided into three groups of green, brown, and red algae based on their pigment. Algae have been reported to have a good effect on some vegetable crops. The oxygen produced by algal photosynthesis prevents anaerobiosis in the root system of the crop. Algae have been reported to release plant growth regulators such as auxin, cytokinin, gibberellin, macro and micro elements, amino acids, vitamins, and abscisic acid in plant cultivation system which affect cellular metabolism in treated plants leading to enhanced growth and crop yield [58].

Algae extract foliar application improved photosynthetic pigments in plants such as beans. Various scientific studies have proven that the efficiency of seaweed products is widely accepted in agriculture and has led to increase crop production per unit area and improved agricultural product quality and increased income levels for farmers around the world [59, 60].

Seaweed fertilizers can be considered biological fertilizer due to their nitrogen, phosphorus and potassium, trace elements, and secondary metabolites similar to plant growth regulators. Marine algae liquid fertilizers include high levels of elements and organic matter transporters such as amino acids and plant growth regulators. Some of these algae are mixed with other organic matter and used for soil fertility, and some are added directly to the farmland, allowing them to absorb rot over time [61]. Many microorganisms, including fungi, cause disease in plants. The lack of low-toxicity products has motivated for new effective and safe technologies to control pathogens. Seaweed extract as a biological product can be used against plant diseases [62].

Betaine and mannitol and some other sugars are substances that cause osmotic balance of plant cells. Use of seaweed extract due to the presence of glycine betaine in the cell reduces the effects of environmental stresses and also increases the tolerance of plants to cold [63].

Algae are important because of their high fiber content, an important role in softening soil texture and maintaining moisture; they are also important for having minerals and trace elements.

The results show that glycine betaine protects the root cell membrane against the damaging effects of heat stress. Some red algae used as biological fertilizers have increased the value and yield of the crop plants [64].

The use of biological fertilizers, such as those derived from algae, in addition to providing nutrients to the plant, causing very little damage to the environment and increase soil

biodiversity. Biological fertilizer use is expected to increase as demand for fertilizers increases. Also, enhancing the efficiency of crop production and energy crisis issue and increasing chemical-fertilizer cost and environmental concerns caused by these fertilizers underscore the importance of biofertilizers [57]. Marine macroalgae have great proficiency in improving soil physical and chemical properties. Most marine algae such as *Enteromorpha flexuosa*, *Ascophyllum nodosum*, *Laminaria digitate*, and *Fucus vesiculosus* are useful in the pharmaceutical industry. However, their use in sustainable agriculture development is still a secondary goal [65].

## Use of Algae in WasteWater Treatment

Wastewater is produced daily from various urban, industrial, and agricultural sources, causing water crisis, and environmental pollution. Conventional methods for wastewater treatment are very expensive and they do not seem to be economically viable [66].

Recently, algae have become important microorganisms for wastewater treatment because they are capable of accumulating plant nutrients, heavy metals, pesticides, and organic and inorganic toxic substances (Table 1). The main advantage of using algal system is that it absorbs solar radiation in the form of energy in its chloroplast organelle and takes CO<sub>2</sub> along with nutrients from wastewater to synthesize their biomass and produce oxygen [67].

As mentioned, algae are capable of photosynthesis and oxygen production. Oxygen from the photosynthesis process can reduce the demand for biological oxygen (BOD) in the effluent. The oxygen released from the algae is sufficient to meet the needs of aerobic bacteria. These bacteria are themselves the main source of CO<sub>2</sub> for algae growth, stimulate the release of vitamins and organic growth factors, and change the pH of the supporting medium for algal growth. Algae can absorb various forms of nitrogen [68], heavy metals [69], and phosphorus [70]. Wastewater naturally contains a lot of nutrients that are used to grow algae. Light and carbon are important factors in the growth of algae [71]. As a result, algae can be used at a low cost to treat wastewater and prevent contamination of aquatic ecosystems. Of course, biomass obtained from algae can also be used in various fields such as biofuel production or aquatic nutrition. The use of green algae such as *Euglena*, *Chlamydomonas*, and *Chlorella* in the outlet channel of large and shallow wastewater storage tanks (wastewater oxidation) is the fastest and least costly way to effectively convert toxic substances into valuable fertilizers. These algae consume nitrates and phosphates for their metabolism activities, releasing oxygen through photosynthesis, and the released oxygen helps aerobic bacteria become active in decomposing wastewater raw materials [72].

Most algae coexist with several microorganisms throughout their lives [8]. Bacteria play an important role in stimulating algae growth, spore germination, morphogenesis, and pathogenicity [12], and also, they increase algae production and help algae perform diverse and complex tasks. For example, algae and bacteria contribute to faster and more efficient removal of organic and inorganic waste and hazardous materials in wastewater treatment [73]. A study was conducted to investigate the relationship between bacterial growth and lipid production in *C. vulgaris* microalgae grown in seafood wastewater effluent (SWE). The results showed that cultivation of *C. vulgaris* in the effluent not only inhibited the growth of bacteria in the division phase but also increased the accumulation of *C. vulgaris* lipids at the death phase. In addition, the lipid content was almost twice as high as the control. The success of this study could extend to the development of wastewater treatment plants to convert SWE nutrients into

**Table 1** The use of algae and microalgae in industry

Algae species	Function	Industrial application	Reference
<i>Gracilariopsis longissima</i> (red algae)	Control pathogens <i>Rhizoctonia solani</i> (Fungi, Ascomycota)	Agriculture	[98]
<i>Chlorella</i> sp. (green algae)	Symbiosis with <i>Nitzschia</i> for domestic wastewater treatment	Wastewater treatment	[76]
<i>C. vulgaris</i>	Using <i>C. vulgaris</i> , the triangular bioreactor was superior for removing ammonia and the cylindrical bioreactor was superior for removing phosphorus.	Wastewater treatment	[99]
<i>Scenedesmus dimorphus</i>	<i>S. dimorphus</i> , ammonia and phosphorus were removed from the wastewater in the cylindrical bioreactor.	Wastewater treatment	[99]
<i>Scenedesmus obliquus</i>	N and P were removed through <i>S. obliquus</i> . It was cultured in urban wastewater. High potential for growth inside wastewater	Wastewater treatment	[100]
<i>Stoechospermum marginatum</i> (brown alga)	Growth, biochemical, and yield were found to be enhanced in <i>Solanum melongena</i> (brinjal)	Fertilizer	[101]
<i>Sargassum wightii</i> (brown alga)	Promoted dry and fresh weight, root, and shoot length of <i>Abelmoschus esculentus</i>	Fertilizer	[102]
<i>Rosenvingea intricata</i> (red alga)	Promoted dry and fresh weight, root, and shoot length of <i>Cyamopsis tetragonoloba</i>	Fertilizer	[103]
<i>Macrocystis pyrifera</i>	<i>M. pyrifera</i> biomass was applied as a thickening agent in cosmetics by other industries.	Cosmetics	[104]
<i>Navicular incerta</i>	Crude lipids 8.76%, crude proteins 50.38%, and carbohydrates 10.84%	Animal feed	[105]
<i>Undaria pinnatifida</i> , <i>Porphyra</i> sp., <i>H. elongate</i> , <i>elongata</i> <i>Undaria</i> , <i>C. crispus</i>	Vitamins, minerals, and edible fiber are high. Calorie is low.	Human food	[41]
<i>H. pluvialis</i> <i>Dunaliella</i> sp.	Formulated feed ingredient	Aquaculture	[31]
<i>Nannochloropsis</i> sp. <i>N. oleoabundans</i> <i>Anabaena azollae</i>	Due to their high oil content, they are suitable as raw materials for biofuels. As a biological fertilizer, it shows liginolysis and releases phenolic compounds, causing more spores of microorganisms.	Biofuel	[106]
<i>Arthrospira</i>	It can grow in extreme conditions that can withstand up to pH 10.	Biofuel	[107]
<i>Synechocystis</i> sp.	The residual untreated organics in the wastewater was further treated in algal.	Wastewater treatment	[67]
<i>K. alvarezii</i>	Enhanced yield and nutritional quality in green gram ( <i>Phaseolus radiata</i> L.) treated with seaweed ( <i>K. alvarezii</i> ) extract	Fertilizer	[108]

highly economical and valuable lipids through the algal bio plant [74]. In fact, the use of live microalgae to eliminate wastes dissolved in aquaculture is an efficient and cost-effective wastewater treatment method [75].

Both open pond and closed pond systems are used for wastewater treatment for economical cultivation of algae. Studies have shown that the biomass produced by *C. vulgaris* when cultured in the continuous system was 130 mg per l per day, which was twice as high as when it was cultivated in the batch system. In general, algal species tend to produce higher biomass



relative to the batch system and are more economical when cultivated in continuous or semi-continuous systems [76].

Since, algae are able to purify contaminated water, it is expected that algae technology would be common in the future of waste water treatment.

## Use of Algae in Aquaculture

Given the rapid expansion of the aquaculture industry, sustainable and inexpensive solutions are important for the development of aquatic feed. Algae are an important source of nutrition for fish due to their essential amino acids, omega-3 fatty acids, pigments, and antioxidant content. Production of aquatic feed from microalgae has the potential to be a complete substitute for fishing food, but it is not economically viable at present, and is currently being produced as aquaculture feed supplement. Despite the economic value of some materials accumulated in microalgae cells, they have not yet been widely commercialized. This is usually due to the high cost of their extraction and purification process [77].

For the use of microalgae in aquaculture, ease of cultivation, non-toxicity, high nutritional value with appropriate cell size and shape, and a digestible cell wall to provide the nutrients are needed [78]. It has also been found that a combination of different algae species provides more balanced nutrition and improves fish growth than the diet consisting of one algae species. Typically, the first stage of aquatic feeding begins with live feed, especially microalgae [79]. Use of algae in aquaculture has a great positive effect on aquaculture including positive effects on weight gain and triglycerides, muscle protein deposition, improved disease resistance, reduced nitrogen production in the environment, increased fish digestibility, hunger tolerance, and overall quality of fish body [80, 81].

Algae have many uses in aquaculture. For example, some algae have a pigment responsible for pink color in salmon. Moreover, astaxanthin is a red-orange carotenoid pigment, and is naturally occurring in certain algae, such as *Haematococcus pluvialis*, causing pink or red in salmon, trout, crabs, and shrimp.

Ornamental aquaculture production is one of the earliest economically viable jobs today. The main attraction of the ornamental fish is their color, and the fish are usually unable to synthesize the carotenoid needed to create the proper color, and must be added to the fish feed along with feeding. *Chlorella* grows well in chemical-rich media and contains the highest amount of chlorophyll compared to other algae. This algae is useful as a source of pigment production and is widely used in the aquaculture industry [82].

Given the importance of the aquaculture industry and the supply of aquatic nutrition in this activity, it is essential to increase production and economic justification, to use a high-efficiency diet, and to reduce feed costs. Therefore, the use of organisms such as microalgae and algae as a supplement to the aquatic diet can be very useful.

## Use of Algae in Biofuel Production

Algae are considered good potential sources for biofuels because of their high oil content, rapid biomass production potential, low cost, and high efficiency [75]. Global sources of fossil fuels are limited and their combustion results in the release of CO<sub>2</sub> and other greenhouse gases that cause climate change, so there is a need for renewable and clean energy sources. Biodiesel

is a non-toxic, biodegradable, and biocompatible fuel that can be used in diesel engines. Biodiesel is free of sulfur and aromatic compounds and emits a small amount of carbon monoxide, hydrocarbons, and pollutants into the environment due to combustion. There are several methods for producing biodiesel, the most common of which are biodiesel from vegetable oils, animal fats, and algae. Biodiesel produced from algae has advantages over its production from plants, some of which are mentioned. The need for large areas for large-scale cultivation of plants for biodiesel production and the water shortage crisis are important reasons to pay attention to new sources such as algae for biodiesel production [83]. Microalgae are able to absorb CO<sub>2</sub> directly from the gases emitted from power plants and factories, and produce significant volumes of biomass and oil using light and quantitative nutrients [84]. The most common biofuels are bioethanol, which can replace fossil fuels. The most important alternative to diesel fuel in Europe is biodiesel, which accounts for 82% of total biofuel production and is growing in Brazil and the USA [85].

To convert algae biomass, the combined algal processing (CAP) pathway is followed. The biomass is dehydrated and exposed to acid pretreatment, and its carbohydrates are decomposed into monomers. Liberated sugars are converted into a wide range of products including ethanol or hydrocarbon fuels, or chemical products. Bioethanol is an alcohol obtained by the fermentation process and is produced mostly from carbohydrates in starchy and sugary plants such as corn, sugar beet, and sugarcane. Bioethanol is widely used in the USA and Brazil [86]. From an economic point of view, the production of ethanol from sugar beet as a raw material is very good because the amount of fermentable sugar that can be used directly and without change is high [87].

## Specific Economic Use of Algae

In addition to what has been said about the use of algae, such as food and medicine, algae also have special economic uses, some of which are mentioned (Figure 3).

Agar is a polysaccharide compound that is extracted from the cell wall of red seaweed, especially *Gracilaria*, *Gelidium* species [88]. This polymer has a wide role in various industries, including the important role of gelatinous properties and food stabilization [89]. The quality of the extracted agar depends on the performance and strength of the gel. Agar extracted from *Gelidium* algae was of better quality, but the large population and massive growth of *Gracilaria* species have made these algae the main source of agar extraction in the world [90].

In the paper industry, the raw material for paper production is wood, but due to the long time that is needed to grow trees and the need to preserve them, it is better to study and exploit new cellulosic sources as a substitute for wood used in the paper industry. One of the non-woody plants that can be used in this industry is the fibers of freshwater or saline algae. The use of algae, in addition to the reduction of the destructive effects of overharvesting of wood from forests, and the extraction of cellulose from its cell wall are easier due to the lack of cellulose in contact with lignin in its cell wall. *Cladophora* are of these green algae [91].

Studies have been performed to use marine brown algae extract as an additive to increase viscosity in cementation materials [92]. A study was performed on seaweed; in this study, brown seaweed was used as an additive to concrete. With a constant ratio of water to cement (W/C = 0.5), marine brown algae are added to produce concrete by producing 2%, 5%, 8%, and 10% of cement content. Hardness tests were performed at 3, 7, and 14 days. The results



**Figure 3** Specific economic use of algae

showed that different strength properties of concrete increase or decrease with the addition of seaweed. Compressive strength increases with the addition of more seaweed. It has also been reported that the maximum load-bearing capacity of a concrete mix beam is higher than that of a conventional concrete beam. This study shows that adding 8% of seaweed to concrete increases the strength properties, and when this additive increases to 10%, the properties start to decrease [93].

The plastic industry is one of the most important industries. However, the impact of plastic waste is a growing concern. The production of bioplastics using algae to solve wastes has received much attention in the world. Algae, especially microalgae, can degrade plastics through enzyme activity, indeed, using plastic polymers as carbon sources [94].

### **Challenges Raised During Use of Algae as a Sustainable Renewable Resource**

Algae can be useful in water sources and treatment plants in some stages. However, they often cause many problems due to their overgrowth, such as changes in taste and odor in the water. The growth of algae in water sources can also increase the temperature and stagnate the water, hence decreasing the number of herbivorous fish [95].

The most important negative effects of algal growth in water treatment plants and water resources can be mentioned as follows: Overgrowth of algae eventually causes the water surface to be covered, and the possibility of light as well as oxygen to penetrate to the underlying layers and the depth of water is eliminated. Failure of oxygen to penetrate deep into the water can eventually lead to the death of fish and aquatic animals [96].

Other adverse effects include unpleasant odors of soil and fish in the water. The main reasons for this odor are Geosmin and MIB, which are found in blue-green algae. Cyanobacteria in the water can cause poisoning in animals and humans. Excessive growth and multiplication of algae block the path of sand filters and equipment used for water treatment and reduce their efficiency. In addition, the accumulation of algae on the filtration filters reduces the washing distance of the membranes and eventually reduces their efficiency. Excessive growth of algae in treatment plants causes the water to become corrosive and damages the treatment equipment. Excessive growth of algae in water sources also causes algal bloom and eventually causes the phenomenon of atrophy and rot of water sources [97].

## Conclusion

Algae are of high economic value and are widely used today in the industrial, agricultural, pharmaceutical, and food sectors, and modern technology is used for the production and exploitation of algae in many countries around the world.

Considering the importance of algae, it is necessary to pay attention to the following points, because non-renewable resources are scarce and some of their use could cause environmental pollution. Renewable sources such as algae and microalgae can be a good alternative to non-renewable resources, because algae are abundantly available and biomass production is high per unit area.

Numerous studies show that they are widely used in the pharmaceutical industry. The world's growing population and the limited arable land available for plant crops in the future will make it difficult for future food production. So, the use of algae will be increased, either directly to feed human or indirectly to feed animals or fish. It can be a low-cost solution to the problem of food supply. We conclude that the extracts derived from seaweeds as eco-friendly biofertilizers can replace chemical fertilizers. They would also play important role in sustainable and organic agriculture.

Therefore, the study of algae in different fields can provide broad perspectives for the use of this organism in different areas of human life, and other organisms.

**Availability of Data and Material** Not applicable

**Code Availability** Not applicable

**Author Contribution** Robab Salami wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript.

Masoumeh Kordi, Parisa Bolouri, and Nasser Delangiz helped with constructive discussions and revised the article

Behnam Asgari Lajayer prepared, edited, and submitted the manuscript

## Declarations

**Ethics Approval** Not applicable

**Consent to Participate** Not applicable

**Consent for Publication** Not applicable

**Competing Interests** The authors declare no competing interests.

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