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# Biotechnological and Commercial Utilization of Algae: A Review

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**Abstract:**

Algae are a diverse group of photosynthetic organisms found in marine and freshwater environments. With a rapid doubling time, they rank among the fastest-growing organisms. Algae utilize various pathways to capture atmospheric carbon dioxide and efficiently convert nutrients into biomass. Recently, their potential for food and fuel production has garnered significant attention. In the energy sector, algae-based biofuels have emerged as sustainable, eco-friendly, and cost-effective alternatives to traditional fuels, including bioethanol, biogas, biohydrogen, biodiesel, and bio-oil. Additionally, algae have been explored for food-related applications, such as producing single-cell proteins, pigments, bioactive compounds, pharmaceuticals, and cosmetics. This review underscores the extensive potential of algae for food and fuel industries while providing insights into commercially available algae-based products.

**Keywords:** Algae, Microalgae, Macroalgae, Biofuel, commercial, Potential

## Introduction:

Algae have long been utilized for their ability to produce high biomass in extreme environments, outperforming cereal-based crops. Classified as third-generation biofuels, algae offer numerous advantages over agricultural crops for energy production. While the concept of using algae for biofuel is not new, the high production costs remain a challenge due to limited cultivation systems. However, advancements in technology are enabling large-scale algae cultivation year-round across diverse climatic zones, from tropical to moderate regions.

Algae also have the unique ability to sequester carbon-rich gases, acting as effective absorbers of carbon dioxide and nitrogen oxides from various sources. Remarkably, 1 kg of algae biomass can fix approximately 1.8 kg of carbon dioxide. Furthermore, algae can grow in wastewater rich in nitrogen and phosphorus, simultaneously producing biofuels and reducing excess nutrient levels in the water[4,5,6].

A vast array of metabolites derived from algae, rich in bioactive compounds, remains largely untapped. For instance, *Haematococcus pluvialis*, a freshwater alga, is a key source of the commercially valuable pigment astaxanthin, while *Chlorella vulgaris* is widely used as a food supplement, and *Dunaliella* species are known for β-carotene production. Marine algae biomass can serve as a versatile feedstock for producing various fuels, including bioelectricity through co-firing, bioethanol, biodiesel, bio-oil via pyrolysis, and biomethane through fermentation.

The market potential for algal biofuels is immense, thanks to their sustainable approach to replacing fossil fuels. Algae typically contain over 50% starch, which can be converted into ethanol. Their cell walls, rich in carbohydrates, make them a viable raw material similar to cellulosic ethanol. Through pyrolysis, algal biomass can also be transformed into organic liquids, such as acetic acid, acetone, and methanol, along with clean and cost-effective gaseous products. Key factors that make algae a strong candidate for bioenergy production include high biomass productivity, ease of mechanical harvesting, and cost-effective production compared to other biomass sources.

**Various Algae-Based Fuels:**

In the modern age, the depletion of fossil fuels and the challenges of global warming have shifted global focus toward generating bioenergy from algal biomass. Enhancing energy access and ensuring energy security are now pivotal strategies for alleviating poverty. Currently, producing biofuels from algal biomass stands as the most viable alternative to reduce fossil fuel dependence and consumption. (Figure 1)

**Biofuels**

Biofuels refer to solid, liquid, or gaseous fuels derived from renewable raw materials. The effectiveness of any conversion process depends on factors such as the type and quantity of biomass, the desired energy output, and the economic value of the final product[9]. Agricultural crops are categorized as first-generation biofuels because they are used for food or feed; however, this creates a competition between food and fuel production, limiting the capacity of these biofuels to significantly contribute to overall fuel consumption.

Unlike biofuels from agricultural feedstocks, algae cultivation does not require agricultural land, avoiding competition with food production. Algae offer several advantages, including high biomass productivity, the ability to treat wastewater, year-round production, and adaptable chemical composition. Furthermore, the oil content of algae can be optimized by modifying cultivation techniques, enhancing their efficiency as a biofuel source.

**Bio-Oil**

Bio-oil is produced through thermo-chemical conversion, a process that transforms biomass into oil, along with char and gas, in the absence of oxygen at high temperatures. Due to its similarity to petroleum oils, bio-oil can serve as a viable substitute[11]. This conversion process involves two main steps: pyrolysis and thermo-chemical liquefaction[12].

Pyrolysis occurs at very high temperatures (350–530°C) and produces three fractions: liquid, gas, and solid. The liquid fraction consists of aqueous and non-aqueous phases, collectively referred to as bio-oil or tar, and requires pre-dried biomass. In contrast, thermo-chemical liquefaction processes wet biomass at lower temperatures (around 300°C) and high pressure (approximately 10 MPa).

Bio-oil contains various organic compounds derived from lipids, proteins, and carbohydrates in algae. Compared to lipids alone, algae yield a higher overall bio-oil output. Studies have explored the use of microalgae for bio-oil production through pyrolysis or thermal liquefaction. For instance, pyrolysis of *Dunaliella* biomass produces hydrocarbons, while bio-oil yields from various algae species include:

- Up to 41% for *Spirulina*[18]
- 24%–45% for *Scenedesmus*[19]
- Approximately 37% for *Dunaliella*[20]
- Up to 49% for *Desmodesmus*[21]

Macroalgae also exhibit significant potential. Liquefaction of macroalgal biomass can yield up to 23% bio-oil[22, 23], with energy recovery reaching 63% in *Laminaria saccharina*[24] and bio-oil yields as high as 79% after hydrothermal liquefaction[25]. Conversely, freshwater macroalgae, such as *Oedogonium* and *Cladophora*, produce lower yields of 26% and 20%, respectively[26].

**Biodiesel**

In recent years, biodiesel has gained widespread attention and is primarily produced from oilseed crops such as soybean, palm, and rapeseed oils[27]. The cost of biodiesel production largely depends on the choice of raw material, which accounts for 50–85% of the total fuel price. For cost-effective production, it is crucial to evaluate feedstock based on productivity, quality, and the potential utilization of by-products[28, 29].

The process of converting lipids, mainly triacylglycerols or free fatty acids, into non-toxic and eco-friendly biodiesel is known as transesterification. In this process, crude algal oil, which has high viscosity, is transformed into low molecular weight fatty acid alkyl esters. Using a catalyst, the crude oil reacts with an alcohol, typically methanol, to produce fatty acid methyl esters (FAME) and glycerol as by-products. While acid catalysts have certain advantages[30], alkali catalysts are widely used due to their efficiency, being up to 400 times faster[31].

Species like *Chlorella vulgaris* and *Chlorella protothecoides*, known for their high oil content, have been extensively studied for biodiesel production. Gülyurt et al.[32]investigated the potential of *Chlorella protothecoides* using microwave-assisted transesterification. Optimum conditions for maximum biodiesel yield included a 9:1 methanol-to-oil molar ratio, 1.5% potassium hydroxide catalyst-to-oil ratio, and a reaction time of 10 minutes.

Microalgal biodiesel primarily consists of unsaturated fatty acids[33]. Algal biomass obtained from wastewater contains a mixture of algae species, resulting in varied fatty acid profiles. For example, Bjerk[43]successfully produced biodiesel using a blend of algae species, including *Chlorella sp.*, *Euglena sp.*, *Spirogyra sp.*, *Scenedesmus sp.*, *Desmodesmus sp.*, *Pseudokirchneriella sp.*, *Phormidium sp.*, and *Nitzschia sp.*.

**Bioethanol**

The production of bioethanol from algae has gained significant attention due to their high biomass productivity, diversity, variable chemical composition, and efficient photosynthetic rates. Algae are considered an ideal source for bioethanol production due to their high carbohydrate and polysaccharide content, as well as their thin cellulose walls. Two primary methods are employed for bioethanol production from algae: fermentation and gasification[42].

In many countries, commercial ethanol is produced on a large scale from sugary and starchy crops through fermentation. For algal bioethanol, the biomass is ground, and starch is

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converted to sugars through enzymatic, acidic, or alkaline methods. Yeast, typically *Saccharomyces cerevisiae*, is added to initiate fermentation, converting sugars into ethanol[43]. The ethanol produced is then extracted and transferred to a distillation unit for further purification.

Research highlights several promising approaches:

- Ueno et al.[44]examined the marine green alga *Chlorococcum littorale* for ethanol production via dark fermentation, utilizing 27% of cellular starch within 24 hours at 25°C.
- John et al.[45]evaluated algal biomass as a renewable feedstock for bioethanol, emphasizing its potential as a sustainable biofuel. Species such as *Dunaliella*, *Chlorella*, *Chlamydomonas*, *Arthrospira*, *Sargassum*, *Spirulina*, *Gracilaria*, *Prymnesium parvum*, *Euglena gracilis*, and *Scenedesmus* have been explored.
- El-Sayed et al.[46]investigated bioethanol production from the seaweed *Ulva lactuca* using fermentation with yeast. Optimization through the Plackett-Burman design and immobilization techniques showed a conversion efficiency of 47.1% for free yeast and 52% for immobilized yeast.

Additionally, Obata et al.[47]studied bioethanol production from brown seaweeds (*Ascophyllum nodosum* and *Laminaria digitata*). These were pretreated with dilute sulfuric acid and hydrolyzed using commercial enzymes, yielding fermentable sugars such as glucose and rhamnose. Fermentation with non-conventional yeast strains, *Scheffersomyces stipitis* and *Kluyveromyces marxianus*, produced ethanol yields of approximately 6 g/L, with *K. marxianus* yielding slightly better results than *S. stipitis*.

**Biobutanol Production**

In regions such as Asia, Europe, and South America, algae cultivation is primarily focused on producing bioethanol and biogas. However, in the United States, algae are gaining recognition for their potential in biobutanol production. For over a century, butanol has been utilized as a transportation fuel and is now considered a promising biofuel. It is seen as a superior alternative to ethanol as a petroleum additive due to its low vapor pressure and high energy density[59].

The production of butanol has economic advantages, as the bacteria involved can digest not only starch and sugars but also cellulose found in algal biomass, making it comparable in cost to ethanol production[60]. Anaerobic fermentation by various *Clostridium* species can produce acetone, butanol, and ethanol (ABE) through a process known as ABE fermentation, which utilizes both hexose and pentose sugars[61]. However, butanol production faces challenges due to fermentation inhibition, which limits yield and productivity.

For instance, butanol has been produced from the fermentation of the alga *Ulva lactuca* using *Clostridium* strains, though yields are relatively low at 0.16 g of butanol per gram of algae, compared to ethanol under similar conditions[49]. Pretreatment of *Ulva lactuca* with hot water, followed by enzymatic hydrolysis using commercial cellulases, has shown promise in producing ABE compounds, achieving a yield of 0.35 g of ABE per gram of sugar[61].

**Algae-Based Non-Energy Applications**

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Algae have immense potential for a wide range of products due to their vast diversity and the ability to modify their chemical composition based on cultivation conditions. However, the exploration of algae-based products remains limited, leaving much of this natural resource untapped. Several factors contribute to this limitation, including economic constraints, regulatory hurdles for product approvals[63], limited public awareness of algae-based products[62], insufficient knowledge of algae cultivation techniques, and inadequate investments in large-scale production facilities.

Among the commercially available algae-derived products, most are used in food applications or as alginates, which are primarily sourced from seaweed. These are moderately derived from natural populations rather than cultivated algae (Table 1).

**Pharmaceuticals**

Algae are abundant in unique biologically active compounds, including both primary and secondary metabolites, making them a promising resource for the pharmaceutical industry[65]. These bioactive compounds are likely a result of the algae's natural habitat in aquatic ecosystems, where they face competitive pressures between producers and consumers. Microalgae, in particular, are a rich source of bioactive compounds that can be harnessed for commercial use. Algae provide a diverse array of pharmaceutical products, proteins, vaccines, and nutrients that are otherwise difficult or costly to produce from animal or plant sources[66, 67]. While the commercialization of pharmaceutical products derived from microalgae is still in its early stages, it holds great potential to become a multibillion-dollar industry in the near future. With their remarkable genetic potential to produce various bioactive compounds, microalgae are positioned at the forefront of biotechnological research.

Table 1. Useful substances present in

| S.No. | Natural substances present inalgae | Different compounds derived from algae |
|---|---|---|
| 1. | Pigments | Astaxanthin, lutein, zeaxanthin, canthaxanthin, chlorophyll, phycocyanin, phycoerythrin, fucoxanthin |
| 2. | Carotenoids | β-carotene |
| 3. | Polyunsaturated fatty acids (PUFAs) | DHA, EPA, ARA, GAL |
| 4. | Vitamins | Biotin, riboflavin, nicotinic acid, pantothenate, folic acid |
| 5. | Antioxidants | Catalases, polyphenols, superoxide dismutase, tocopherols |
| 6. | Other | Antimicrobial compounds, toxic products, aminoacids, proteins |

Various unicellular algae, including *Chlorella vulgaris* and *Chlamydomonas pyrenoidosa*, have demonstrated antibacterial properties against a range of pathogens, including both gram-positive and gram-negative bacteria, through their cell extracts and growth media extracts. Additionally, there have been some reports of in vitro antifungal activity from the extracts of green algae and diatoms. Certain blue-green algae and microalgae, such as *Ochromonas sp.*

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and *Prymnesium parvum*, are known to produce toxic substances that hold significant potential for pharmaceutical applications[70, 71]. Many species of *Cyanobacteria* are recognized for producing intracellular and extracellular metabolites with a broad spectrum of biological activities, including antibacterial, antifungal, and antiviral effects[72]. (Table 2)

Table 2: Biotechnological applications of bioactive

| S.No. | Algae Specis | Different compounds | Uses |
|---|---|---|---|
| **1.** | Spirulina platensis | Phycocyanins | Nutraceuticals, cosmetics |
| **2.** | Chlorella vulgaris | Ascorbic acid | Health food, food supplement, food surrogate |
| **3.** | Haematococcus pluvialis | Carotenoids, astaxanthin | Nutraceuticals,, pharmaceuticals, additives |
| **4.** | Odontella aurita | Fatty acids | Pharmaceuticals, cosmetics, baby food |
| **5.** | Porphyridium cruentum | Polysaccharides | Pharmaceuticals, cosmetics, |
| **6.** | Dunaliella salina | Carotenoids | Nutraceuticals,, food supplement, feed |

**Cosmetics**

Microalgae species, such as *Arthrospira* and *Chlorella*, are well-established in the skincare market, with companies like LVMH (Paris, France) and Daniel Jouvance (Carnac, France) developing their own microalgal cultivation systems. Microalgal extracts are included in various cosmetic products, including anti-aging creams, rejuvenating treatments, sun protection products, and hair care items[86]. As awareness of skin cancer and photoaging caused by sun exposure has increased, there has been a growing demand for sunscreen products in recent years.

Amino acids, such as mycosporine, have gained commercial interest for their natural UV-blocking properties in sunscreens. Many microalgae produce metabolites like sporopollenin, scytonemin, and mycosporine, which protect them from UV radiation while allowing visible light, essential for photosynthesis, to pass through[87]. Algae components are also commonly used as thickening agents, water-binding agents, and antioxidants in cosmetics[88]. Various algae extracts are found in face and skin care products, with species such as *Chondrus crispus*, *Ascophyllum nodosum*, *Alaria esculenta*, *Spirulina platensis*, *Nannochloropsis oculata*, *Chlorella vulgaris*, and *Dunaliella salina* being utilized.

For example, *Spirulina* is featured in beauty products like the *Spirulina Firming Algae Mask* by Optimum Derma Aciditate, which improves moisture balance and enhances skin immunity, and the *Spirulina Whitening Facial Mask* by Ferenes Cosmetics, which contains proteins and herbal extracts to improve skin complexion and reduce wrinkles without side effects. Codif Recherche & Nature (Paris, France) markets a product made from *Phormidium persicinum*, called *Phormiskin Bioprotech G*, known for its unique photo-protective properties[89]. (Table 3)

**Pigments**

Microalgae are rich in pigments associated with light absorption, including chlorophyll (the primary photosynthetic pigment), phycobiliproteins, and carotenoids. Carotenoids extracted from microalgae are widely used in the market. For instance, *β-carotene* from *Dunaliella* serves as a vitamin supplement in health foods,

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while *lutein*, *zeaxanthin*, and *canthaxanthin* are used in pharmaceuticals and for enhancing chicken skin color. *Astaxanthin*, extracted from *Haematococcus*, is used in aquaculture to provide a natural red color for fish like salmon.

Phycobiliproteins, such as phycocyanin and phycoerythrin, which are unique to algae, are already utilized in food and cosmetics[90, 91]. The antioxidant properties of carotenoids are particularly important for human use, as they act as free radical scavengers and have anti-cancer effects. Among natural antioxidants, *astaxanthin* stands out for its potent effects. Due to its antioxidant properties and role as a precursor to vitamin A, *β-carotene* is now commonly used in health foods. Pigments extracted from microalgae are also commercially used as natural food colorants.

Table 3: Sources of UV-screening compounds from

| S.No. | UV screening compound | Algae |
|---|---|---|
| 1. | **Sporopollenin** | Characium terrestre, Coelastrum microporum, Enallax coelastroides, Scenedesmus sp., Scotiellopsis rubescens, Dunaliellasalina, Chlorella fusca |
| 2. | **Scytonemin** | Chlorogloeopsis sp., Calothrix sp., Scytonema sp., Nostoccommune , Nostoc punctiforme |
| 3. | **Mycosporines** | Ankistrodesmus spiralis, Chlorella minutissima, Chlorella sorokiniana, Dunaliella tertiolecta, Isochrysis sp., Corethron cri- ophilum, Stellarima microtrias, Alexandrium catenella |

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colorants and cosmetic ingredients.

**β-Carotene**

Carotenoids are commonly used as natural food colorants, additives in cattle feed, and in various cosmetics. Nutritionally, carotenoids like *β-carotene* serve as a provitamin A[68]. The physical properties of natural *β-carotene* make it a preferable choice over synthetic alternatives. Specifically, *β-carotene* is fat-soluble. Recently, the National Cancer Institute recognized *β-carotene* as an anticancer agent, and numerous studies have highlighted its effectiveness in managing cholesterol and reducing the risk of heart disease. These new findings position *β-carotene* as a promising product with potential for increased demand in the commercial market.

**Astaxanthin**

Astaxanthin is another carotenoid derived from microalgae, with various industrial applications. This pigment, a keto-carotenoid, is primarily obtained from the alga *Haematococcus pluvialis* and is produced under stress conditions. During these conditions, the algae cells transition from thin, flagellated forms to red, thick-walled resting stages, making up about 4-5% of the dry weight[96]. Astaxanthin is commonly used as a food colorant, a feed additive in the poultry industry, and as a supplement for fish such as salmon, trout, and shrimp[96].

**Phycobiliproteins**

The levels of various elements, such as phycobiliproteins, in algae are influenced by environmental factors like light intensity and the spectral quality of light. For instance, when *Spirulina platensis* is cultivated under different light intensities, the amount of phycocyanin ranges from 11% to 12.7% of dry weight[101]. *Spirulina* and *Porphyridium* are two common microalgae commercially cultivated for phycobiliprotein production. These pigments have significant potential in the food industry as natural colorants, in cosmetics, and as diagnostic tools in biomedical research, such as fluorescent markers[102]. For example, phycocyanin is marketed under the brand name "Lina Blue" by Dainippon Ink and Chemicals for use in products like popsicles, candies, cold drinks, dairy items, and chewing gum. The price of phycobiliproteins can range from US$ 3 to US$ 1500 per mg for certain cross-linked pigments[103].

**Algae-derived compounds for human usage**

The use of algae as a food has been dated back to 2500 year ago in Chinese literature [108]. Many macroalgae (seaweeds) are consumed in various partsof Asia as food directly and edible in small amount by native people of countries like Africa, South America and Mexico due to their vitamins and nutritional value [109].They can also be added into different foods like pastas, snacks, gums, beverages, noodles, cookies [110, 111]. A blue green alga named Spirulina platensis is acquiring worldwide attention as food additive due to its high nutritional value as a food to human. It has been demonstrated as a rich source of proteins [112], polyunsaturated fatty acids [113], pigments [114, 115], vitamins and phenolics [112, 116]. These days Chlorella is also being majorly sold out in food store and as a fish feed, like Spirulina [117]. Currently, the microalgal market is ruled by Chlorella and Spirulina [118, 68], dueto their high protein value, nutritional value and ease of growing. Their biomass is sold as tablets, capsules and liquids, to be used as nutritional supplement [118]. The biomass of microalgae composed of three major portions: proteins, carbohydrates, and lipids [119]. In the table 5, compositional analysis of various microalgal biomass in terms of main components is given.

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Table 4. Various high-value compounds derived from

| S.No. | Product group | Applications | Examples (producer) |
|---|---|---|---|
| **1.** | Phycobiliproteins | Pigments, cosmetics, vitamins | Phycocyanin (Spirulina platensis) β carotene (Dunaliella salina) astaxanthin(Haematococcus pluvialis) |
| **2.** | Polyunsaturated fatty acids (PUFAs) | Nutraceuticals, foo dsupplements | EPA-(Chlorella minutissima) DHA-(Schizochytrium sp.) |
| **3.** | Vitamins | Nutrition | Biotin -(Euglena gracilis) α-tocopherol) -(Euglena gracilisa Vitamin C-(Prototheca moriformis) |

Table 5. Commercialization of important microalgae for nutrition (Adapted from

| S.No. | Algae | Algae based companies | Different algae products |
|---|---|---|---|
| 1. | Spirulina (Arthrosphira) | Hainan Simai Pharmacy Co. (China) Earthrise Nutritionals (California, USA) Cyanotech Corp. (Hawaii, USA) | powders, tablets, powders, tablets, powders, beverages, tablets, chips, pasta |
| 2. | Chlorella | Taiwan Chlorella Manufacturing Co.(Taiwan) | tablets, powders, nectar, noodles,powders |
| 3. | Dunaliella salina | Cognis Nutrition and Health(Australia) | powders b-carotene |

**Fertilizer**

Both macroalgae and microalgae contain various compounds that support plant growth, including promoting germination, leaf or stem development, and flowering, and can also serve as biological protectants against plant diseases[68]. These algae are used in several coastal regions. After extracting oil and carbohydrates from algae, a significant amount of nutrients remain in the spent biomass. This leftover biomass can be repurposed as a biofertilizer, enhancing the economic value of algae by allowing its reuse in cultivation after nutrient extraction. The remaining biomass can be utilized as fertilizer. Many cyanobacteria are capable of fixing atmospheric nitrogen, making them effective biofertilizers. They play a crucial role in preserving soil fertility and enhancing rice growth and yield when used as natural biofertilizers[121]. Nitrogen, after water, is the second most important factor for plant growth in fields, with fertilizers typically meeting this requirement[122]. Blue-green algae (BGA) such as *Nostoc*, *Anabaena*, and *Tolypothrix* are capable of fixing atmospheric nitrogen and are used as inoculants for growing paddy crops in both upland and lowland conditions[123].

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**Fibres for Paper**

Sulfur-containing polysaccharides provide structural stability to most algae[124]. Algae that contain cellulose can potentially be used as a feedstock for paper production, although there are few examples of algae being utilized as a non-wood fiber source. For instance, algae collected from a municipal wastewater treatment plant were incorporated into a 10% pulp mix by Ververis et al.[125], which led to a significant increase in the mechanical strength of the paper and a 45% reduction in material costs due to decreased brightness. This resulted in a 0.9-4.5% reduction in overall costs. However, this concept remains largely within the research phase, and commercialization efforts need further attention.

**Processed Food Ingredients**

Agar, alginates, and carrageenans are some of the most valuable products derived from algae, known for their gelling and thickening properties. In recent years, there has been significant growth in algae research and development, particularly in areas such as protoplast fusion, macroalgal cell cultures, and transgenic algae[68].

**Agar**

Agar, obtained from macroalgae, has numerous applications in food products such as frozen foods, desserts, candies, and fruit juices. It is also used in various industries, including paper sizing, textile printing, and molecular biology as agarose. Additionally, it plays a role in biomedical fields, where it is used to produce capsules, tablets, and anticoagulants[125].

**Carragenans**

Carrageenan, a water-soluble polysaccharide derived from algae, is more commonly used than agar as an emulsifying and stabilizing agent in a variety of food products. κ- and ι-carrageenans are often utilized in items such as jellies, jams, desserts, and meat products due to their thickening properties. In addition, carrageenans have been explored for various pharmaceutical applications, including antiviral, antitumor, and anticoagulant effects.

| S.No. | Cyanobacteria | Growth enhancers |
|---|---|---|
| **1.** | Cylindrospermum sp. | Vitamin B12 |
| **2.** | Tolypothrix tenuis | Vitamin B12 |
| **3.** | Nostoc muscorum, Hapalosiphon fontinalis | Vitamin B12 |
| **4.** | Nostoc, Hapalosiphon | Auxin like Indole-3-acetic acid<br>indole-3-propionic acid or 3-methyl indole |

**Alginate**

Alginate, a compound derived from brown algae, is valued in the textile industry for sizing cotton yarn and is highly regarded for its gelling properties. Its chelating ability and capacity to form highly viscous solutions make it a promising candidate for use in the food and pharmaceutical industries.

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## Conclusion

In the field of algae, there is a pressing need to advance research and development efforts to overcome technological challenges, as algae have the potential to yield novel chemicals and bioactive compounds. The applications of algae are vast within the biotechnology sector, and it is essential to tap into their rich diversity for a wide range of uses. Algae show great promise as sources of biofuels, high-value molecules, nutraceuticals, and bioactive metabolites, which could lead to the discovery of new drugs. To fully realize their potential, there is a need for complete utilization of algal biomass and further exploration of their diverse applications.

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