ISSN: 0973-4929, Vol. 20, No. (**3**) 2025, Pg. 1036-1055

Current World Environment

www.cwejournal.org

Microalgae Biomass Production: Cultivation Techniques and Applications

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Abstract

Microalgae biomass production provides a sustainable option for various industries, utilizing advanced cultivation methods to generate valuable compounds. Microalgae biomass is abundant in proteins, lipids, and pigments, making it suitable for diverse applications, including biofuels, animal feed, nutraceuticals, and cosmetics. *Arthrospira* (Spirulina), *Chaetoceros*, *Chlorella*, *Dunaliella*, and *Isochrysis* are a few of the main microalgal species used to produce commercial products. The potential of microalgae biomass production lies in its sustainability, scalability, and versatility. By growing microalgae in salt water or wastewater, freshwater demand can be decreased, and CO_2 can be captured, thus minimising climate change. However, issues such as pollution control, harvesting, and dewatering must be overcome to fully utilise its potential. This review provides an overview of microalgae biomass production, cultivation techniques, and applications, highlighting opportunities and challenges. It talks about how research and development are going right now and stresses the need for more creativity to get over financial and technological obstacles. This review attempts to aid in the creation of sustainable solutions for a variety of industries, including biofuels and nutraceuticals, by investigating the possibilities of microalgae biomass production. With continued research and innovation, microalgae biomass production can play a significant role in shaping a more sustainable future.

Article History

Received: 17 November 2025
Accepted: 07 January 2026

Keywords

Biomass;
Biofuel;
Cultivation Techniques;
Microalgae;
Photobioreactors.

Introduction

The advancement and widespread implementation of clean technologies for energy generation present a challenge for researchers and a priority for energy system operators. Biomass from various origins, with distinct properties and energetic transformability, is recognised as a key source of renewable energy. The term "microalgae" typically denotes eukaryotic

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Doi: http://dx.doi.org/10.12944/CWE.20.3.6

microalgae and prokaryotic cyanobacteria in the field of applied biology. In common usage, "algae" does not denote a specific taxonomic category but rather a collection of aquatic creatures that participate in photosynthesis, a process that uses chlorophyll a, the pigment responsible for half of Earth's photosynthetic activity, to decrease carbon dioxide and generate oxygen. These organisms display a diverse size spectrum, from micrometres to several tens of meters in the case of certain algae.[1] According to Masojídek and Torzillo these creatures are common and found in practically every habitat, from arid deserts to the bitterly frigid polar areas. Photosynthetic microalgae were the first organisms to provide the Earth with oxygen, which made it possible for other types of aerobic life to evolve over time. Microalgae are also big producers of O_2 and consumers of CO_2, which is why they have been popular in recent decades as one of the best ways to turn solar energy into biomass.[2]

Microalgae are photosynthetic microorganisms, either prokaryotic or eukaryotic, that exhibit fast development and may thrive in many settings due to their unicellular or simple multicellular organisation and minimal growth requirements.[3] Microalgae possess extraordinary potential as a bioresource, as they exhibit a higher biomass productivity than terrestrial plants.[4] Microalgae hold considerable biotechnological significance due to their abundant supply of bio*molecules* that offer health and nutritional benefits.[5] It consists of proteins, carbohydrates, and lipids that can be turned into biofuels and other useful products. These products could replace a lot of crude oil and meet the needs for food supplements, animal feed, colourants, enzymes, and many other useful chemicals.[6] Algal cells store a lot of lipids, which have been the subject of most published research on biodiesel generation methods.[7,8] Microalgae biomass contains a variety of biocompounds, including long-chain polyunsaturated fatty acids, carotenoids, astaxanthin, chlorophyll, and antioxidants. These substances are used in food and cosmetics, human nutrition, and the diets of fish and animals. Microalgae have great promise as a future source for biofuel production, as well as in the areas of protein and sustainability.[3,9–11]

Light, temperature, carbon dioxide supply, culture medium composition, pH, bioreactor features, and many more parameters affect the biochemical content and growth of microalgal biomass, which in turn depends on the species.[12] Light is a crucial element in the autotrophic development of microalgae. Photosynthesis enables light-dependent microalgae to assimilate carbon dioxide into their biomass and convert light energy into chemical energy through molecular bonds, facilitating growth and division. Both the light and dark periods make use of the energy that has been stored in *molecules*.[13,14]

According to Maier *et al.*,15 microalgae enhance nutrient cycling, soil aggregation, and microbial community dynamics by fixing atmospheric CO_2 is converted into organic carbon by photosynthesis. In recent decades, a new approach to CO_2 sequestration and nutrient removal from wastewaters has been developed through the cultivation of photosynthetic microorganisms.[15,16] Microalgae and cyanobacteria, which grow autotrophically, lower atmospheric concentrations of carbon dioxide by absorbing it from the air or from flue gas emissions etc.[1,17,18]

The review is carried out using a thorough analysis of the pre-reviewed literature on algae, applications, cultivation modes, and culture technology. Algae were utilised as a natural resource due to the biological activity of their isolated metabolites and their potential health benefits.[19] This review will describe recent applications of bioactive compounds from algal species.

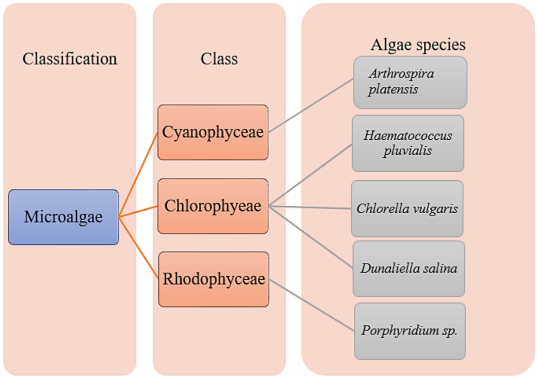

Fig. 1: Classification of microalgae for biomass production and value-added compounds.

Strain Selection

There are between one to ten million different types of microalgae on Earth, and scientists have found more than 40,000 of them.[20] According to Abdulla *et al.*,[21] microalgae provide several benefits over conventional energy crops, including being the quickest-growing photosynthetic organisms and being able to be grown in environments with minimal nutrients. Growing on non-arable ground with low-quality water, such as brackish water, municipal wastewater, or industrial effluents, increases oil output, speeds up growth and photosynthetic rate, and eliminates food competition.[3,22] *Chlorella protothecoides* is considered an optimal feedstock for biodiesel production, as it can accumulate up to 55% lipid when cultured heterotrophically under nitrogen limitation.[23] Furthermore, specific microalgal species are capable of attaining elevated concentrations of particular biofuels. Traditional communities have utilised microalgae for an extended period. Certain species of blue-green algae, including *Nostoc, Arthrospira* (*Spirulina*), and *Aphanizomenon*, have been used for human consumption for many generations.[24]

Cultivation Mode

Autotrophic Culture

This method is most effective when executed in an outdoor area because of the ample, unobstructed availability of sunshine and inorganic carbon dioxide compounds. Microalgal cells grown in a photoautotrophic environment use light for their energy source and carbon dioxide for their carbon source; this method is the easiest for developing microalgae. Due to the large amount of material required, growing autotrophic microalgae necessitates a major investment in expensive energy sources such as carbon and phosphorus. Recent studies have focused on identifying cost-effective sources of carbon and nitrogen to promote microalgae growth, particularly in relation to carbon and nitrogen pollution.[25]

Heterotrophic Culture

In contrast to autotrophic microalgae culture, heterotrophic culture operates under dark conditions, employing organic carbon sources like glucose and other organic compounds, along with an external carbon supply, which may lead to significant biomass accumulation of lipids.[26] Microalgae cultivated for biomass and lipid productivities in heterotrophic conditions under optimal culture parameters typically exceed those of other algal species.[26,27] Heterotrophic cultures demonstrate a greater accumulation of biomass lipids and accelerated cell development rates in comparison to autotrophic cultures. Light is essential for photoheterotrophic organisms to utilise organic *molecules* as a carbon source. In heterotrophic cultures, carbon *molecules* such as glucose, glycerol, and acetate serve as sources of energy and carbon in the absence of light. To prevent bacterial contamination, selecting heterotrophic algae species with a high adaptability to their environment is essential.[28] Nitrogen concentration has a significant influence on lipid accumulation across various cultivation methods, including both autotrophic and heterotrophic approaches. The nitrogen content of the medium influences the lipid quantity in microalgal cells. The elevated heterotrophic culture productivity has generated considerable interest in identifying microalgal strains that can produce elevated lipid content under optimal conditions for heterotrophic development.

Mixotrophic Culture

Microalgae exhibit growth capabilities in both photoautotrophic and heterotrophic conditions. In a mixotrophic ecosystem, organisms utilise both sunlight and dark conditions to acquire carbon from inorganic and organic sources. The concentration of organic carbon in the atmosphere influences aerobic metabolism.[29] The intensity of light influences the fixation of artificial carbon during photosynthesis.[30] The primary distinction between photoheterotrophy and mixotrophy lies in the fact that photoheterotrophy primarily derives its energy from light. Conversely, mixotrophy can utilise organic substances as an alternative.[31] Organic *molecules* facilitate the growth of microalgae in mixotrophic farming, suggesting that their development is not solely dependent on photosynthesis. Light availability is not essentially a limiting factor for microalgae development. Inadequate or excessive illumination levels may lead to a reduction in photo limitation or photo inhibition in mixotrophic cultures.[32] Inorganic waste components can serve as cost-effective nutrient sources for mixotrophic microalgae. To enhance biomass production in mixotrophic cultures of *Chlorella pyrenoidosa*, substantial quantities of ammonium and phosphate, present in aerobically digested sewage sludge, were introduced. This method facilitated the growth of microalgae and the production of lipids by utilising total N, PO_4, and other nutrients present in the mixed waste culture solution, eliminating the need for additional nutrient sources.[33]

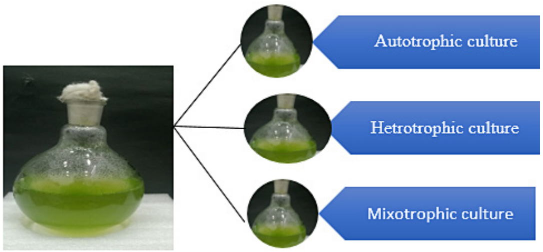

Fig. 2: Various cultivation modes of microalgae

Cultivation Method

Microscopic autotrophic or heterotrophic photosynthetic animals that grow in water are called microalgae. They can be single- or multicellular. Microalgae comprise more than 40,000 different species, according to Fuentes-Grünewaldet *al.*,[34] and their lipid content makes up a large portion (20-50%) of their overall biomass.[35] Microalgae are not like watery plants in that they don't have real embryos, roots, stems, or leaves. However, they can use CO_2, water, and sunshine to build up biomass through photosynthesis.36 Some different methods for growing microalgae have been described.[37] The culture strain type, the variety of nutrients, and the cost of the investment are the major things that determine the cultivation process. It may be put into two primary groups: closed systems and open systems.

Closed System

Vertical Tube Photobioreactor

The vertical tube photobioreactor is designed in two types: bubble column and airlift column. Both kinds of photobioreactors share a common characteristic: an air sparger fastened to the reactor's base improves mass transfer by creating air bubbles to stir the algae and culture media. The bubble column reactor looks like a cylinder-shaped container that doesn't have any walls inside. The fluid flows through it mainly because of the air bubbles that are created. In addition to good mass transfer, this type of photobioreactor has a high surface area vis-à-vis volume ratio and other benefits. Usually, the generator is twice as tall as it is wide, and the light source comes from outside. In order to improve mixing and photosynthesis, the "light flash effect" makes it easier for algae cells to move from areas with light to areas with dark lines running through them. It's important to keep an eye on the gas flow rate in this setup because it changes the light and dark cycle.[38] A closed photobioreactor device can be used to grow *Spirulina*, and every two to five days, it can double the amount of biomass it has.[39,40]

Horizontal Tube Photobioreactor

The horizontal tube, also known as a tubular reactor, was the pioneer closed reactor model designed for growing microalgae. It is composed of long, horizontal tubes that can be arranged in various ways to form walls, helices, or panels. Because of the large surface area needed, this setup needs a lot of land. When the tube is set up this way, the width can be smaller because the light source can reach the culture liquid over a long distance. Microalgae that need sunshine are the only ones that can grow in this type of reactor. This reactor design involves exposing the culture medium to light as it circulates through the tubes, and then pumping it back into the reservoir. To prevent microalgae flocculation, it is critical to keep the reactor's flow regime extremely turbulent.[37]

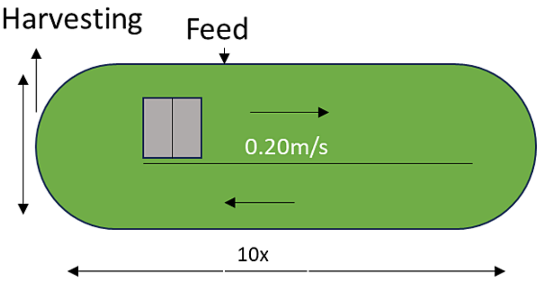

Fig. 3: Detail drawing of Raceway Pond

Open System

Adeniyi *et al.*,[41] say that the open pond system (OPS) is the best way to grow a lot of algae in natural areas of water like small ponds, circular ponds, and raceway ponds. The raceway ponds (Figure 4) are the most popular way to grow plants because they use less energy and don't need as much cost or upkeep.[42,43] However, wind currents, leaks, and animals can make the racing pond not work as it should.[44] The choice of equipment for growing and making algae biomass for energy is a very important problem. The methods used on an industrial scale currently are open ponds because they are more cost-effective. The way they're made is usually very simple. Some of these are ground tanks with a lot of space and a depth of up to 0.5 m. A paddle stirrer is used to stir the water manually. It's designed to look like a pond or a racetrack.[45]

Culture Parameter

Light

Like all plants, micro-algae engage in photosynthesis, meaning they take in inorganic carbon to transform it into organic matter. The energy driving this reaction originates from light, necessitating careful consideration of intensity, spectrum quality, and photoperiod. Light intensity plays a crucial role, with requirements differing significantly based on the depth and density of the algal culture. With increasing depths and higher cell concentrations, it is essential to enhance the light intensity to ensure adequate penetration through the culture. For instance, 1,000 lux is appropriate for Erlenmeyer flasks, while larger volumes necessitate 5,000-10,000 lux.[46] Light serves as the essential energy source for the process of photosynthesis in microalgae. Light acts as a crucial element influencing the growth performance of microalgae. Microalgae exhibit no net growth when light intensity is relatively low, such as below the compensation point.[47,48] Beyond the light compensation point, algal growth can increase with rising light intensity, and the peak rate of photosynthesis is achieved at the light saturation point. Beyond the light saturation point, further increases in light intensity will not enhance the growth rate, as this can lead to photo-inhibition.[48]

Temperature

The metabolic rate of an organism is typically influenced by temperature. Controlled environments typically maintain low temperatures ranging from 18 to 23°C. The transfer of algal starters should be conducted in the early morning when scaling up for mass production. This timing helps to mitigate stress caused by sudden temperature increases.[46] Microalgal growth typically experiences an exponential increase as temperatures rise to an optimal level. Beyond this point, further temperature increases do not enhance microalgal growth and may instead result in biomass loss.[47] Research indicates that microalgae are capable of surviving at temperatures below the optimal range and above freezing. Furthermore, numerous species of microalgae have been identified that can readily endure temperatures up to 15°C lower than their optimal level.[8] For the majority of algal species, maintaining a temperature range of 20°C to 30°C is essential for optimal growth.[35] To guarantee that the temperature remains within the optimal range, it is essential to consider the implementation of suitable water-cooling systems in outdoor cultivation setups, as overheating of the culture can cause challenges.[15]

pH and Salinity

Various media exhibit distinct pH levels. The pH values during cultivation are variable due to their dependence on the balance of CO_2 in the media. The optimal pH range for freshwater microalgal cultures is typically between 6.5 and 7.5.[49] Most species of microalgae exhibit tolerance to a wide range of pH values, with this tolerance being dependent on the specific species. In a study by Lam and Lee,[50] the cultivation of microalgae in media with a pH range of 3, 4, 5, 6, 7, 8, and 9 revealed no significant differences in growth characteristics. The optimal pH for microalgae is species-dependent, with *Spirulina* requiring a pH range of 8 to 9.5, while *Chlorella* thrives at a pH of 6.5 to 7.5.[50] During the cultivation of microalgal cultures, salinity may rise as a result of evaporation. Excessive salinity levels can induce salinity stress, potentially altering the morphology and structure of algal cells due to the differential water pressure between the culture medium and the cells.[8] The occurrence of adverse salinity stress inhibits the growth of algal cells.

Nutrients

The typical composition of microalgal biomass is represented by the formula $C_{106}H_{263}O_{110}N_{16}P_{19}$. Therefore, the macronutrients must include N and PO_4, with SI also being necessary for marine algae. Furthermore, trace elements, including Fe, Mn, Mg, K, B, Mo, Co, and Zn, are also required. Accessible agricultural fertilisers can be utilised as sources of nutrients. Based on the composition of microalgae, the estimated nitrogen requirement for fertiliser is between 8 and 16 tonnes N per hectare.[51] To address the deficiencies in seawater, it is essential to enrich algal cultures with nutrients. Macronutrients consist of nitrate, phosphate (in an estimated ratio of 6:1), and silicate. Silicate is utilised specifically for the growth of diatoms, which employ this compound for the formation of an external shell. Micronutrients include a range of trace metals as well as vitamins such as thiamine (B_1), cyanocobalamin (B_{12}), and occasionally biotin. A variety of enrichment media have been widely utilised and are appropriate for the cultivation of most algae, including the Walne medium and Guillard's F/2 medium. Several detailed recipes for algal culture media are outlined by Vonshak.[52] In some ways, these new developments in algal culture offer likely solutions to the numerous issues facing aquaculture.[46]

Applications

Food and Nutrition

A variety of bioactive compounds, lipids, proteins, and microalgae have various bioactivities, making them a potential food and ingredient source. For human health, protein is essential. Several factors have brought attention to microalgae's potential as a protein source. According to Ciani M *et al*.,[53] photobioreactors are often more efficient than plant or animal cultivation when it comes to producing microalgal protein. They have higher photosynthetic efficiency, can manage the process, and use nutrients better to generate food year-round. Photobioreactors can be installed in urban areas as well as on non-arable terrain. The use of wastewater and other non-potable water sources to grow microalgae is a viable option; however, this method is limited to non-food uses, such as treating wastewater and making agricultural goods at the same time. Furthermore, saltwater may be used to cultivate marine microalgae, which are abundant in proteins and polyunsaturated fatty acids. The rational amino acid contents and excellent digestibility of microalgal proteins are additional benefits. Additionally, microalgal proteins are healthy to ingest, as certain strains, such as *Nostoc* and *Arthrospira*, have been used as food for millennia.[53]

The marketing of microalgal biomass is currently limited; thus, further research is needed to evaluate the nutritional value and safety of additional strains of microalgae. This knowledge would allow for the production of meals incorporating microalgae. A few strains have achieved commercial success. *Arthrospira platensis*, commonly referred to as *Spirulina*, and *Chlorella vulgaris* are recognised as food-producing species. *Haematococcus pluvialis* and *Dunaliella salina* are noted for their carotenoid content. Marine strains from the algal genera *Nannochloropsis*, *Tetraselmis*, and *Isochrysis* serve as animal feeds, while *Tetraselmis* chuii is currently marketed as human food within the European Union.[54] Astaxanthin, produced and stored by the microalga *H. pluvialis*, is of particular importance since it is one of three primary food components that have been identified as being ready for further investigation and has tremendous promise as a specialty food ingredient.

Microalgae have a wealth of beneficial bioactive components, including vitamins, in addition to proteins and carotenoids. Vitamin E serves as an example of a compound produced by photosynthetic organisms, comprising eight distinct lipid-soluble chemicals, including tocopherols and tocotrienols. A recent study identified α-tocomonoenols in microalgae, with n110 α-tocomonoenol as the predominant isomer in *Chlorella* sorokiniana, *Nannochloropsis limnetica*, and *Tetraselmis suecica*, while this molecule was primarily observed in terrestrial plants.55 The food sector is increasingly focused on bioactive substances derived from microalgae, including polyunsaturated fatty acids, phycobiliproteins, and polyphenolic compounds. Most of the bioactive chemicals that microalgae make are stored inside their own cells. To enhance bioavailability when consumed or to recover and purify the drug, a cell wall disruption step is typically required. Recent research found that a synergistic impact combining ultrasonic and enzymatic hydrolysis was responsible for the successful extraction of omega-3 fatty acid-rich lipids from the microalga *Nannochloropsis gaditana*. A notable enhancement in oil production of 29% was realised through the integration of ultrasonic waves (37 kHz, 140 W) with enzymatic hydrolysis utilising viscozyme (55 °C, 6 h), in contrast to employing either method in isolation.[56]

Algal biomass is an appropriate feed additive in several nutritional and toxicological studies.[57] According to Certik and Shimizu58 algae have a positive impact on both the internal and external aspects of animals' bodies. Internally, they supply a wide range of vitamins, minerals, and essential fatty acids, while externally, they help with weight management, immune response, and fertility. Additionally, algae promote healthy skin and a shiny coat.[58] The green unicellular microalgae *Chlorella vulgaris* has garnered significant attention because of various potential applications, namely treating wastewater, feeding fish, and extracting important chemicals from biomass.[59] As the demand for foodstuffs with more natural ingredients continues to rise, almost 30% of microalgal cultivation goes towards animal feed.[60] One healthy phytonutrient found in *Chlorella vulgaris* is known as *Chlorella* growth factor (CGF). CGF is a rich source of nucleic acid-associated compounds, including peptides, proteins, amino acids, vitamins, and essential carbohydrates.

Pharmaceuticals and Health Care

The majority of microalgae include antimicrobial properties, including linolenic acids, which can kill methicillin-resistant *Staphylococcus aureus*. Polyunsaturated aldehydes, glycosides, terpenes, and chlorophyll a derivatives are among the bioactive compounds that microalgae use to exert their antibacterial effects.[61] To prevent bacteria from growing and viruses from attaching, microalgae release certain chemicals.[62] An ethanol extract of *C. vulgaris* has been shown to have antibacterial activity against *Staphylococcus aureus*, According to Ibrahim and Dineshkumar *et al*. *C. vulgaris* exhibits antibacterial capabilities against both Gram-positive and Gram-negative bacteria.[63,64] According to Mostafa SS.,[65] Chlorellin is a powerful antibacterial agent. The bioactive compounds contained in the blue-green microalgae *Spirulina* have therapeutic properties, including antioxidants and anti-inflammatory actions.[19,66–68] *Spirulina* biomass electrospun into biocompatible nanofibers with polymers produces adaptive scaffolds that are hydrophilic, have a wide surface area, and can support cell adhesion and proliferation more effectively than before.[69]

Tables 1: Applications and properties of microalgae

Microalgae	Compound name	Properties	Applications
Chlorella sp., Chaetoceros sp., Euglena gracilis	Carbohydrates Exopolysaccharides (EPS) e.g., β-glucan	Biofilm adhesion, antiviral activity, anticancer effect, and chemical sorption.[70;71,72]	Wastewater treatment, soil health, medical applications, and the food sector (thickeners, preservatives)
Limnospira platensis, *Porphyridium* sp.	Sulfated polysaccharides, e.g., Spirulan	Anti-inflammatory, antiviral, and anti-adhesive properties.[70;72;73]	Use in medicine (herpes simplex treatment, bacterial and tumour cell adhesion prevention)
Chlorella sp., *Nannochloropsis* sp., *Schizochytrium* sp., *Phaeodactylum tricornutum*, *Porphiridium cruentum*	Lipids and fatty acids Omega 3 PUFAs e.g., DHA, EPA, ARA	Immunomodulatory and cardioprotective characteristics.[70;74;75]	Human functional foods (omega-3 supplement); animal feed (aquaculture, livestock
Chlorella sp., Scenedesmus spp., Selenastrum sp. (Monoraphidium sp.), L. platensis	Pigments Chlorophylls e.g., chlorophyll a, chlorophyll b	antioxidant, proliferation of tissues promotion, and pigmentation influence.[70;72;76;77]	Beverage and food dye (green pigmentation); smell masking (personal care goods); ulcer therapy, cosmetics
Haematococcus pluvialis,	Astaxanthin (carotenoid)	Strong antioxidant, lipid-lowering action,	Pharmaceuticals, food supplements, sports nutrition,

Chlorella zofingiensis		and colouring impact[70;78]	animal nutrition, food and beverage colouring (red pigmentation), aquafeed colouring (salmonids), and cosmetics
Dunaliella salina	β-carotene (provitamin A)	antitumor, antioxidant, and ocular health[70;79]	Cosmetics, colouring for food, feed for livestock, and food supplements
Anabaena vaginicola	Lycopene	Antioxidant, skin protection against UVR	Colouring for foods and cosmetics (sunscreen, anti-ageing)
Chlorella pyrenoidosa, C. minutissima, D. salina, L. platensis	Polyphenolic compounds e.g., phenolic acids, flavonoids, Proteins, peptides, amino acids,	Antimicrobial, anti-inflammatory, and antioxidant[72;80]	Nutritional supplements
Anabaena spp., C. vulgaris, D. salina, Scytonema sp., L. platensis, Glenodinium foliaceum	Mycosporine-like Amino Acids (MAAs) e.g., Shinorine, palythine, mycosporine-glycine	Antioxidant, anti-photoaging,anti-cancer, anti-desiccant,wound-healing, and UVR protection for skin[81;82;83]	Pharmaceuticals (fibroblast growth stimulant), cosmetics (sunscreens, antioxidants), and additives to shield materials from UV light
Cyanobacteria (L. platensis, Aphanizomenon flos-aquae, etc.), P. cruentum, P. aerugineum	Phycobiliproteins (PBP), e.g., phycoerythrin (PE), phycocyanin (PC)	Antioxidant, hepato-protective, anti-inflammatory, immuno-modulatory, anti-cancer[72;84;85]	Food, cosmetic, and textile dyes, fluorescence probes, medications
Most microalgae (Tetraselmis suecica, Dunaliella tertiolecta, Skeletonema marinoi, etc.)	Vitamins e.g., vitamins B1, B2, B3, B6, B9, B12, C, E.	Antioxidant[70;86;87]	Animal nutrition, cosmetics, and food supplements (including vegan populations)
Most microalgae (*Phaeodactylum sp., Thalassioria sp., Amphora sp., Achnanthes* sp., etc.)	Minerals and trace elements Macrominerals e.g., calcium, nitrogen, magnesium, phosphorus, potassium, sodium, sulfur	Nutrients that are necessary for metabolism[86;70;87;88]	Biological stimulants and macronutrients (food and feed industry)
Most microalgae (*Tetraselmis chuii,*	Microminerals e.g., cobalt, copper,	physiological roles (as components of	Cosmetics, food supplements, and bio

Phaeodactylum sp., Aphanothece sp., Navicula sp., Thalassiosira sp., etc.)	iodine, iron, manganese, molybdenum, selenium, zinc	hormones and cofactors for enzymes) [86;70;87;88]	stimulants
Chlamydomonas reinhardtii, *Chlorella ellipsoidea, cyanobacteria* (*Synechococcus sp., Anabaena* spp., A. *platensis*), P. *cruentum*, D. *tertiolecta*, *Nannochloropsis oceanica*	Enzymes e.g., cellulases, amylases, galactosidases, proteases, lipases, antioxidant enzymes, carbon accumulation enzymes	Carbohydrate, protein, lipid, phenolic molecule, antioxidant, and carbon fixation degradation, hydrolysis, or catalysis[89]	Biofuels, medical applications, bioremediation (macronutrients, heavy metals, antibiotics, phenol, colourants), and the food and feed sectors

Biofuel and Energy

The third generation of biofuels will be made using microalgae as its feedstock.[90] Generations three and four both involve the conversion of microalgal and macroalgal biomass residuals, including lipids, into biofuel.[91] Autotrophic microalgae can produce biodiesel, biogas, biohydrogen, bioethanol, butanol, bio-oil, char, and electricity by utilising carbon dioxide to synthesise carbohydrates, proteins, and lipids.[92,93] *Chlorella protothecoides*, a prevalent microalga, is suitable as a biodiesel feedstock due to its ability to achieve a lipid content of 55 per cent under nitrogen-limited heterotrophic conditions.[23] Biodiesel derived from microalgae is generally produced through a two-step process: initially, lipids are extracted from cells of microalgae, and then transesterification of the lipid fraction with alcohol in the presence of catalysts.[94,95] report that *Scenedesmus obliques* can produce biohydrogen at a rate of up to 300 μmol H_2/mg $Chl^{-1}h^{-1}$. Benemann (2000) describes one method that converts carbohydrates and other biomass into biohydrogen via fermentation and/or photo fermentation.[96] Another method involves the separation of water into hydrogen and oxygen through direct or indirect water bio photolysis.[94] also discuss two such methods.[97] indicate that specific microalgal species can produce biogas at a rate of 0.70 L biogas/g VS (0.43 L CH4/g VS). The large-scale growth of *Nannochloropsis salina* in a photobioreactor at 35 °C exemplifies this phenomenon.

Biofuels are produced from biomass materials, which consist of organic compounds sourced from plants, algae, or processed animal by-products. Synthetic fuels are produced from commercial feedstock materials, distinguishing them from non-renewable energy sources like natural gas, petroleum, and coal.[98] Microalgae can contain over 80% oil by weight in their dry biomass. This oil can be converted into biodiesel through a process analogous to that used for other feedstock oils.[99] Microalgal lipids can be classified into two main categories: polar lipids, including glycerophospholipids, which are crucial for cellular structure, and nonpolar lipids, such as triacylglycerols, which are mainly responsible for energy storage. Polyunsaturated fatty acids (PUFAs) like eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA), and docosahexaenoic acid (DHA) are often found in structural lipids, namely polar lipids, which include long chains of fatty acids. The development of mitochondrial super complexes is a crucial process that PUFAs contribute to A.[100] The lipid content of microalgae typically ranges from 7 to 65%,[101] while the oil content of each algal species is affected by growing circumstances and the development phase.[102] *Chlamydomonas reinhardtii*, *Chlorella* sp., *Spirogyra* sp., *Porphyridium cruentum*, *Spirulina* platensis, *Dunaliella salina*, *Bellerochea* sp., *Chaetoceros* sp., *Rhodomonas* sp., and *Scenedesmus* sp. are some of the microalgae species that are appropriate for biomass biofuel production.[103] According to Ryckebosch *et al*.,[104] some microalgae species, such as Bacillariophyta, *Chlorophyta*, *Cryptophyta*, *Phaeophyta*, and *Rhodophyta*, can be utilised to produce omega-3 polyunsaturated fatty acids.[104] According to Brindhadevi *et al*.,[105] the best microalgae species to use as feedstock in biodiesel synthesis are those having a greater mass percentage of lipid content.[105] The fermentation of microalgae into alcohol is best accomplished using microalgae that are rich in carbohydrates.[106]

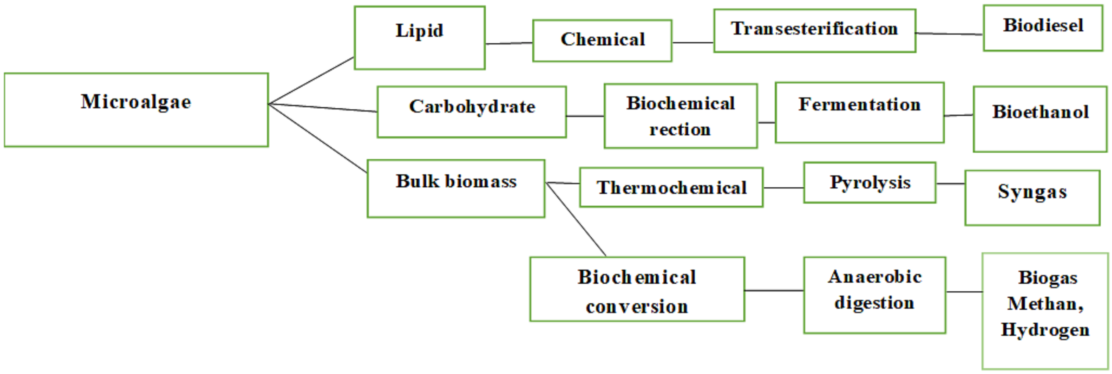

Fig. 4: Conversion technologies of microalgal biomass to renewable fuel.

Microalgae in Cosmetics

Arthrospira and *Chlorella* are two of the most well-known microalgal species used in skin care products.[107] Cosmetics companies like LVMH in Paris and Daniel Jouvance in Carnac, France, have even invested in microalgal manufacturing systems. The majority of skin care products that include microalgae extracts are emollients, anti-irritants in peelers, anti-ageing creams, and rejuvenating or regenerative care products. Products for sun protection and hair care also contain microalgae. Product claims include the following: a protein-rich extract from *Arthrospira* (Protulines, Exsymol S.A.M., Monaco) that tightens the skin and prevents the formation of striae; and an extract from *Chlorella vulgaris* (Dermo *Chlorella* Codif, St. Malo, France) that encourages collagen synthesis in the skin, supporting tissue regeneration and reducing wrinkles.[108] Proteins, fatty acids, carotenoids, and chlorophyll are examples of secondary metabolites produced by microalgae. Microalgal secondary metabolites not only repair and heal skin and stop inflammation, but also exhibit anti-blemish and anti-microbial properties.[109] S. platensis, which is high in proteins (50-70%), may be employed as a bioactive chemical to reverse ageing and prevent the formation of wrinkles.[110–113] Extracts from *Chlorella vulgaris* can promote skin collagen production, skin tissue support, and new-tissue rebirth.[111] found that extract from *Dunaliella salina* increased cell proliferation and enhanced energy metabolism. When exposed to ultraviolet light, the algae *Chlorella vulgaris*, *Nostoc*, and *S. platensis* increase their production of the antioxidants, chlorophyll and carotenoids. Diatoms like *Odontella aurita* are rich in beneficial fatty acids, including PUFAs, SFAs, MUFAs, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Several components of microalgae extracts interact with different proteins on the skin to form a protective gel that eventually prevents moisture loss. A study by Ryu B *et al*.,[114] found that *Synechocystis* sp., for instance, has potent antibiotic activity against *E. coli*, *Candida albicans*, *Staphylococcus aureus*, and *Aspergillus niger*. It can also help maintain the equilibrium of the skin's flora by shielding it from microorganisms.[110]

Anti-Ageing Mechanism of Microalgal Compounds

Aesthetics used to the skin to counteract the signs of ageing brought on by both external (such as pollution and smoking) and internal (such as inherited tendencies) causes of skin ageing. For example, they may delay the onset of age-related decline, which would improve the consumer's quality of life and boost their confidence.[115] The brown *macroalgae Macrocystis* pyrifera included two antioxidant compounds that were recently discovered: phloroeckol and tetrameric phloroglucinol. Phlorotannins may have an anti-ageing impact on the skin due to their antioxidant and antidiabetic properties. According to Ramos-e-Silva *et al*.,[115,116] anti-ageing products can utilise extracts from several species of *Monodus*, *Thalassiosira*, *Chaetoceros*, and Chlorococcum to improve collagen stimulation. *Arthrospira* and *Chlorella vulgaris* extracts, correspondingly, have anti-ageing and anti-wrinkle characteristics, according to research conducted by Borowitzka, Wang, Kim *et al*.[9,110,117] Brown macroalgae help keep skin healthy and cells regenerating because they are rich in minerals, vitamins, and essential fatty acids like omega-3 and omega-6. The activation of matrix metalloproteinase (MMP) by free radicals in skin fibroblasts can damage collagens, cell membranes, and cell nuclei. Algae extracts have the potential to alleviate UV-induced skin problems, including stratum corneum thickening, rough texture, wrinkles, and flaccidity by raising fibroblast collagen and elastin levels and inhibiting matrix metalloproteinase (MMP) activity.[118]

Application of Microalgal Compounds as Agents for Skin Lightening

Cosmetics that nourish the skin and help it retain its protective barrier function so that it always looks healthy. Indications for their use include atopic dermatitis and dry skin, which can occur in people with certain genetic abnormalities (e.g., a mutation in the filaggrin gene that produces natural moisturising factors)[115,119,120] According to Hagino and Saito certain proteins and hydrolysates obtained from the genera Porphyra, *Spirulina*, and *Chlorella* exhibit a strong affinity for the epidermis and hair, thereby promoting moisture retention and maintaining optimal viscosity.[121] More skin gloss and moisturising activities were seen in the Porphyra-containing cosmetics group compared to the control group. *Spirulina*-containing hair care products offer a moisturising sensation, shine, easy combing, and pleasant sensory properties. Cosmetics that block the tyrosinase enzyme, which in turn stimulates whitening and prevents hyperpigmentation of the skin. An unmixed extract of *Nannochloropsis* oculata containing zeaxanthin, an anti-tyrosinase ingredient, was patented for use in creams.[122]

Photoprotection Potential of Microalgal Products

Microalgal products protect the skin from photoaging, sunburn, photodermatoses, and skin cancer with UV filters that are generally recommended.[123–125,121] found that certain algae may absorb UV light and inhibit melanin production. The keratinous tissue benefits from Chlorogloeopsis sp. extract because it protects against photo-ageing, wrinkles, and skin sagging caused by ultraviolet A and B radiation (the generation of free radicals upon exposure to UV).[126] An SPF-only formulation including just organic and inorganic filters could be just as effective as one incorporating Isochrisis algae in blocking UV transmission. According to Lotan A[127] *Nannochloropsis* algae also effectively blocked the transmission of UVA and UVB rays. The inclusion of cyanophyceae in sunscreen formulations demonstrated enhanced absorption in the UVB-UVA range (290 to 400 nm) compared to a commercial formulation, as well as improved absorption in the visible spectrum (400 to 650 nm).[126] Additionally, mycosporine-like amino acids (MAAs) that absorb ultraviolet light are produced by the cyanobacterium *Nostoc* sp. R76DM.[67,126]

Conclusion

In modern times, algae have gained recognition as a biomass type that possesses exceptional energy potential. While most biorefineries operate on a smaller scale, some organisms are cultivated on a larger scale for feedstock or food processing. One potential sustainable growth path that has recently surfaced is the production of microalgae biomass, which has several potential uses in different sectors. Advanced and developing biotechnologies hold potential for application in the food and pharmaceutical sectors to enhance the efficient production of bioactive carotenoid compounds sourced from microalgae like *Chlorella* sorokiniana and cyanobacteria like *Nostoc* commune. Potential for large-scale production has been demonstrated by the culture techniques, which include photobioreactors, open ponds, and hybrid systems. A wide variety of products may be made from microalgae biomass, including biofuels, animal feed, medicines, and beauty products. Advanced and developing biotechnologies hold potential for application in the food and pharmaceutical sectors to enhance the efficient production of biologically active carotenoid compounds sourced from microalgae and cyanophyceae. The biotechnological relevance of microalgae has increased due to their ability to create bioactive chemicals. It can be used in various ways to improve life quality. Despite their biochemical richness, only a few are examined for their metabolites and chemical makeup. There are several benefits to producing important bioproducts at the same time. The obstacles and restrictions that must be overcome for microalgal-based metabolites to be widely used in the pharmaceutical and healthcare sectors are discussed. This calls for ongoing research and equipment.

Acknowledgement
The authors would like to thank the Principal, C.M.P. Degree College, Prayagraj, for allowing the PhD research work.

Funding Sources
The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest
The authors do not have any conflict of interest.

Data Availability Statement
This statement does not apply to this article.

Ethics Statement
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement
This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from other Sources
Not Applicable

Author Contributions
- **Shantwana Singh:** Data Collection, Writing and Editing.
- **Khushaboo Soni:** Supervision
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- **Payal Chaurasia:** Methodology.
- **Sanjay Singh:** Conceptualisation, writing original draft.

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