

Exploring the Innovative Biotechnological Potentials of Microalgae: A Comprehensive Review

Mahavir M. Sharma, Harshkumar Brahmbhatt

Department of Pharmacy, Sumandeep Vidyapeeth Deemed to be University, Vadodara, Gujarat, India

Abstract

Many of the unique bioactive chemicals found in marine species have exceptional promise for biotechnological innovation. Among them, microalgae have generated a great deal of attention as viable options for creating novel industrial uses. Numerous bioactive substances, including antioxidants, immunostimulatory agents, antiviral and antibiotic compounds, hemagglutinins, peptides, polyunsaturated fatty acids, biofuels, proteins and natural colors, are produced in large quantities by these photosynthetic microbes. The search for ecologically friendly, high-value, and sustainable bioproducts has led to a noticeable increase in interest in microalgal biotechnology in recent years. Microalgal biomass is in high demand because of its numerous uses, many of which are still being thoroughly studied by scientists. As effective light-energy and carbon dioxide converters, microalgae produce more biomass than terrestrial plants and are becoming more widely acknowledged for their adaptability in a variety of biotechnological fields. These include the production of renewable bioenergy, pharmaceutical research, nutraceuticals, animal feed additives, environmental cleanup, and even new treatment strategies for viral diseases like COVID-19. This analysis highlights the growing significance of microalgal biotechnology in influencing sustainable industrial practices and next-generation bio-based solutions by synthesizing current advancements in its use across several industries.

Key words: Biomass, microalgae biotechnology, unicellular photosynthetic

INTRODUCTION

Algae are an extremely varied group of creatures that display a broad range of morphological, structural, and metabolic traits. Both microalgae and macroalgae, which might be unicellular, multicellular, colonial, filamentous, leafy, or branched, are included in this category. Some microalgae are able to group together to create colonies and filaments that are visible to the unaided eye.^[1] *Macrocystis pyrifera*, sometimes referred to as gigantic kelp, is one of the biggest kinds of macroalgae, reaching up to 60 m in length. On the other hand, freshwater or soil-dwelling microalgal species like *Chlorella* have spherical cells that are usually 2–10 µm in diameter.^[2]

While certain species exhibit mixotrophic or heterotrophic metabolic capacities, most microalgae are photoautotrophic, using photosynthesis as their main energy source. Microalgae often show less cellular differentiation and specialization than higher

terrestrial plants. All algal taxa use chlorophyll as their primary photosynthetic pigment, which allows them to absorb sun energy. Furthermore, there may be accessory pigments such as phycobiliproteins and carotenoids that improve light absorption over a wider spectrum.^[3]

Algal biotechnology, or the technological exploitation of algae, including both macroalgae and microalgae, and their derivatives for a variety of purposes, has seen a notable increase in attention in recent years.^[4] Due to their exceptional photosynthetic efficiency, microalgae have been a focus of both scientific and industrial study. Using sunshine, carbon dioxide (CO₂), and vital nutrients, these unicellular

Address for correspondence:

Mahavir M. Sharma, Department of Pharmacy,
Sumandeep Vidyapeeth Deemed to be University,
Piparia, Vadodara - 391760, Gujarat, India.
Phone: 09727264003.
E-mail: mahavir.svp@gmail.com

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organisms may produce a significant amount of biomass in aquatic settings.

Basic metabolites including carbohydrates, lipids, and oils are abundant in this microalgal biomass and may be processed to produce a variety of high-value goods. Because of their metabolic adaptability, microalgae have great potential in a wide range of fields. The manufacturing of industrial raw materials, medicines, nutraceuticals, and renewable biofuels is a notable example of uses. Furthermore, microalgae are essential for aquaculture, environmental cleanup, and even public health programs – such as the latest investigations into their potential for creating COVID-19 and other disease therapies.^[5]

Research in this area is developing quickly due to the wide range and multidisciplinary possibilities of microalgal uses. The increasing amount of scholarly research and technical advancements devoted to realizing the full potential of microalgal biotechnology demonstrates the dynamic and expanding character of this field of study. The current study builds on this basis by synthesizing the most recent developments in microalgal biotechnology from a variety of industrial sectors. It seeks to be a useful tool for directing strategic choices in the future that are necessary to maintain and improve the continued success of research and applications pertaining to microalgae.^[6]

Microalgae have diverse biotechnological applications across various industries.

Environmental

The use of microalgae in the cleanup of contaminated aquatic and atmospheric environments is growing. They have established themselves as an important instrument in environmental biotechnology due to their remarkable ability to absorb atmospheric CO₂ and to remove a wide range of pollutants from different effluent sources, such as industrial discharges, biological treatment systems, and agricultural runoff. Numerous studies have shown how microalgal systems may help address a variety of ecological issues brought on by human-induced industrial and agricultural processes.^[7]

The technique of using microorganisms, either alone or in cooperative groups, to reduce or change contaminants in effluent streams is known as bioremediation. This ecologically friendly method uses these organisms' natural or genetically modified metabolic processes to break down, change, or absorb dangerous materials, including those from aquaculture and other industrial systems.^[8]

Degradation of the environment, especially air and water pollution, is a serious worldwide problem that is made worse by rising carbon emissions. The existing state of the

natural biosphere has not been enough to slow down the sharp increase in atmospheric CO₂ levels and the ensuing disturbance of the global carbon cycle. Given this, microalgae have become a very attractive scientific and technical option for capturing carbon, providing a biologically based approach to atmospheric decarbonization.^[9]

The difficulty increases when dealing with industrial wastewater since different microalgal strains have variable resistance and absorption capacities, and contaminants are diverse. The capacity of the microalgae to absorb, break down, or metabolize particular harmful chemicals in the wastewater is a major factor in the effectiveness of pollutant removal; thus, strain selection and process optimization are essential elements of effective remediation procedures.

Food production

Microalgae are extremely beneficial for human consumption because of their ability to create nutrient-dense food items with a balanced mix of proteins, carbs, fatty acids, and other vital micronutrients.^[10] Microalgal species' high biodiversity offers a great deal of promise for species bioprospecting, highlighting the value of native strains and their potential for a wide range of biotechnological uses. Microalgae are being explored for integration into the human food supply chain, a process that has historical precedent, due to its intrinsic nutritional and functional qualities. Notably, since before the early 20th century, species such as *Spirulina* and *Nostoc* have been ingested as staple foods.^[11]

The adaptability of microalgal biomass in affecting food rheology and product development is demonstrated by recent advances. For instance, *Chlorella vulgaris* and *Arthrospira platensis* have been added to 3D-printed baked products, such as cookies, to help with thermal resistance and structural stability when baking. Although adding microalgae to bread recipes did not dramatically impact textural characteristics such as chewiness or hardness, it did cause noticeable changes in appearance, with the crust and crumb taking on greenish or yellow tints as a result of the algae's natural coloration.^[12]

A thorough approach to the development of microalgae-based foods must take into account every step of the production process, including shelf life and product stability. Over time, functional enrichment with lyophilized and encapsulated *Scenedesmus obliquus* in chocolate bars showed little peroxide production and oxidative stability. Similarly, after 28 days of storage, yogurt enriched with 0.25% *Spirulina* showed less whey separation and maintained a greater moisture content.^[13] *Spirulina* LEB-18 greatly improved physical characteristics including sedimentation rate, hygroscopicity (by about 10%), and solubility when added to chocolate milk. This further highlights the potential of microalgae as useful components in innovative food systems.

Utility manufacturing

The need to lessen dependency on plastics made from petrochemicals has become more urgent as the world moves away from fossil fuels. Plastic pollution has serious negative effects on the environment, especially in landfills and marine environments, which exacerbates ecological imbalances and market vulnerabilities. At the regional, national, and international levels, these growing concerns – particularly in the packaging sector – have sparked a flurry of policy-driven and regulatory measures meant to promote sustainable alternatives.^[14]

The creation of bio-based polymers – materials made from renewable biological sources that may undergo biodegradation – is one viable remedy. These polymers fall into three main categories: (1) Fully renewable, biodegradable polymers, (2) petroleum-based but biodegradable polymers, and (3) hybrid systems that include components from both renewable and petroleum sources.^[15] The use of microalgae as a platform for the manufacturing of sustainable bioplastics is one of the most inventive strategies. It has the added benefit of directly capturing CO₂ from the atmosphere during growing, which helps with climate mitigation.

Numerous approaches have been investigated for turning microalgae into bioplastics. These include using microalgal biomass directly as a structural element in bioplastic formulations, combining materials derived from microalgae with traditional polymers, using biorefinery techniques to extract and change important metabolites, and using cutting-edge genetic engineering to create microalgal strains that can naturally synthesize biopolymeric precursors. When combined, these tactics offer a state-of-the-art approach to finding sustainable resource management and environmentally benign, circular bioeconomy solutions to plastic pollution.^[16]

Aquaculture

Omega-3 polyunsaturated fatty acid synthesis by microalgae offers strong support for their use as dietary supplements in animal and human nutrition. Genera including *Phaeodactylum*, *Chaetoceros*, *Nannochloropsis*, *Pavlova*, *Isochrysis*, *Chlorella*, *Tetraselmis*, *Skeletonema*, and *Thalassiosira* are especially well-known among the wide variety of species investigated for this purpose. Their remarkable nutritional profiles, which contain a wealth of colors, vitamins, trace minerals, and antioxidant chemicals, are the main reason for their extensive usage.^[17]

Many more microalgal taxa, such as *Anabaena*, *Nostoc*, *Botryococcus*, *Synechococcus*, *Chlamydomonas*, *Scenedesmus*, *Perietochloris*, and *Porphyridium*, have shown promise for the production of a variety of bioactive compounds in addition to these often researched species.

These contain strong antioxidants, immune-modulating substances, anti-inflammatory chemicals, and precursors to important vitamins. Among these bioactives, β-carotene, lutein, astaxanthin, chlorophyll, and phycobilins are noteworthy; they all play a major role in the creation of nutraceutical products and functional foods that promote health.^[18]

Pharmaceutical and health

Significant therapeutic promise is demonstrated by a wide variety of algae species and their metabolites. Microalgal biomass was first used in formulations including pills, powders, and aqueous supplements to study its potential medical uses. Research on finding and using bioactive chemicals from algae for pharmacological purposes has significantly increased in recent years. Fatty acids, phycobiliproteins, polysaccharides, phenolic compounds, and carotenoids are some of the most researched medicinal ingredients; each is essential for promoting health and preventing illness. A diverse range of secondary metabolites with strong bioactivities is produced in large quantities by algae.^[19]

The biosynthetic capabilities of microalgae, in particular, allow them to produce intricate bioactive compounds that are challenging to duplicate using traditional chemical synthesis. These include a range of pharmacologically active compounds, hormones, enzymes, neuro- and hepatotoxins, monoclonal antibodies, subunit vaccinations, and antibiotics.^[20] Their great potential in drug development and biological innovation is highlighted by their adaptability.

Numerous health advantages are provided by the pigments obtained from microalgae, which provide defense against long-term illnesses including cancer, heart disease, neurological problems, and vision impairments. Furthermore, because of their quick growth kinetics, simple and affordable cultivation requirements, and the ability to perform post-translational modifications that are more similar to those of mammalian systems than prokaryotic hosts, microalgae are very effective platforms for the production of recombinant proteins^[21] [Figure 1].

Cosmetics and cosmeceuticals

Cosmetics are defined as any substance or combination that is meant to be applied to the epidermis or another exposed regions, including the lips, external genitalia, teeth, and oral mucous membranes. These products have several functions, such as washing, adding scent, changing look, protecting against environmental damage, enhancing skin health, and reducing body odor. Cosmetics with biologically active ingredients, or “cosmeceuticals,” are intended to provide pharmacological effects or therapeutic advantages.^[22]

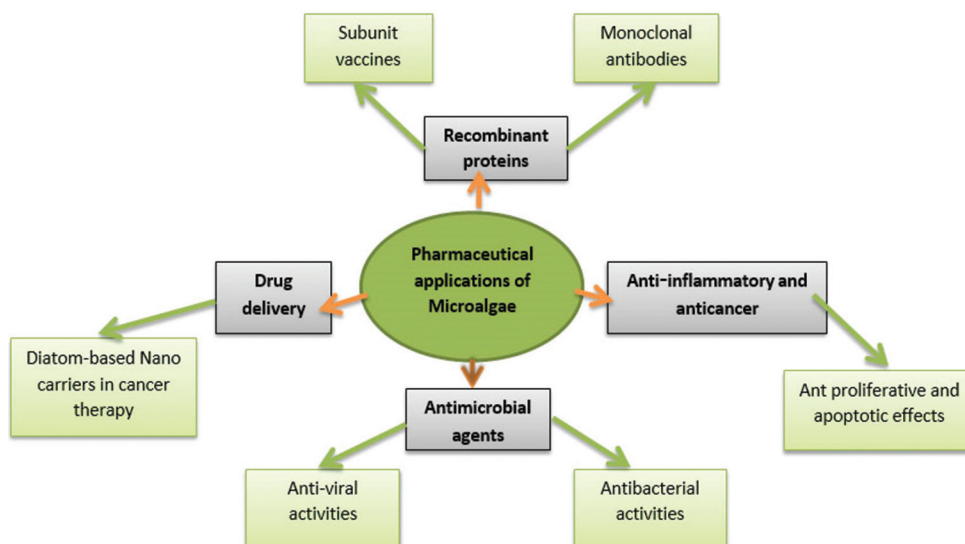


Figure 1: Pharmaceutical applications of microalgae.

Because of their many uses, microalgae and their bioactive ingredients are being used more and more in cosmetic compositions. They serve as antioxidants, free radical scavengers, immunological boosters, stress reducers, odor neutralizers, sources of color for cosmetics, ultraviolet protectors, and anti-aging agents. Active ingredients from microalgae have been shown to provide a variety of dermatological advantages, including avoiding skin imperfections, mending tissue damage, treating seborrhea, reducing inflammation, hastening wound healing, and preserving ideal skin hydration.

Microalgae and macroalgae are widely used in cosmeceuticals because of their photoprotective, anti-aging, moisturizing, and antioxidant qualities.^[23] Algae are mainly used in extract form to lessen the possibility of impurity while making a variety of goods, such as moisturizers, sunscreens, anti-aging creams, skin sensitizers, viscosity enhancers, and hair care products.

Covid-19 treatment

With the capacity to murder hundreds of thousands of individuals, the coronavirus illness is now the most serious global health emergency, making the development of efficient treatment measures imperative. According to research, among the primary reasons for dying for individuals with COVID-19 is acute respiratory distress syndrome (ARDS), which is directly related to cytokine storm syndrome. Because of the overproduction of pro-inflammatory cytokines and chemokines brought on by this cytokine storm, the immune system becomes too activated, causing serious lung injury.^[24]

A carotenoid with well-established therapeutic uses, astaxanthin is widely recognized for its strong antioxidant, immunomodulatory, and anti-inflammatory properties.

This diagram shows the applications of microalgae in the pharmaceutical industry progress from an overall (at the industry level) to specific applications, displayed from inside to outside. The natural source of this chemical is the microalga *Haematococcus pluvialis*. According to this research, giving COVID-19 patients astaxanthin may reduce the flood of cytokines and lower the risk of acute lung injury and ARDS.^[25]

Specialized proteins called lectins have the ability to bind certain mono- and oligosaccharides. Crucially, cyanovirin-N, a lectin that was separated from the cyanobacterium *Nostoc ellipsosporum*, has proven to be effective against a variety of viruses, including human immunodeficiency virus (HIV), influenza, and Ebola. Furthermore, carrageenan-a sulphated polysaccharide derived from microalgae has been shown to inhibit viral attachment, transcription, and replication within host cells.^[26] In addition, a polysaccharide called calcium spirulan, which is isolated from spirulina, has an inhibitory effect against the reproduction of a number of viruses, including influenza, measles, and HIV.

Antimicrobial substances

Many microalgal extracts have a wide range of bioactive qualities, such as antiviral, antibacterial, antifungal, and antiprotozoal effects. Phenolic chemicals, volatile halogenated hydrocarbons, fatty acids, and indoles are some of the bioactive substances that have been found. Furthermore, some cyanobacterial species, such *Prymnesium parvum* and *Ochromonas* sp., produce strong toxins that may find use in medicine.^[27]

Antiviral activities

Usually, viral infections go through three different phases.

First, the virus attaches itself to the cell surface to enter the host cell. In the next phase, the virus grows within the host cell. Finally, the third stage allows the infection to propagate by releasing just become viral particles into the surrounding tissue.^[28] Microalgal-derived antiviral medications function by concentrating on various stages of the infectious cycle. Sulfated polysaccharides, for instance, are known to suppress the first stage by preventing the virus from adhering to host cells.

Antibacterial activities

The essential need for the development of new antimicrobial medicines is highlighted by the current recognition of antibiotic resistance as a significant obstacle to the efficient treatment of infectious illnesses. Numerous fatty acids obtained from *Chlorella* species have been found to have strong antibacterial properties in recent studies. Both Gram-positive and Gram-negative bacterial strains may be inhibited or eliminated by these microalgal-derived free fatty acids, according to available data.^[29] Microalgae and their bioactive components have shown strong anti-biofilm qualities in addition to their antimicrobial effectiveness, which is important for managing and preventing chronic infections. Dental plaque production, a biofilm mostly formed on tooth surfaces by *Streptococcus mutans* and *Lactobacillus* species, is a relevant example. By interfering with the development of these bacterial biofilms, extracts from *C. vulgaris* and *Dunaliella salina* have demonstrated encouraging promise in reducing dental caries.^[30]

Bioenergy^[31]

Following the Second Industrial Revolution, there was a sharp increase in the use of fossil fuels due to the fast urbanization that followed. Through emissions like sulfur dioxide, the burning of these carbon-based energy sources causes severe air pollution, which negatively affects vulnerable people and degrades the ecosystem. Furthermore, a major contributing factor to the escalation of Climate change and the greenhouse effect is the consequent buildup of CO₂ in the atmosphere. Since fossil fuels are limited, non-renewable resources, their ongoing exploitation has led many countries to invest in sustainable energy alternatives, among which biofuels have shown great promise.

The evolution of biofuel production has been divided into four generations: The first uses food crops, the second uses agricultural residues that are unfit for human consumption, the third uses leftover microalgal biomass, and the fourth generation investigates biomass derived from genetically modified microalgae. The world community now sees algae-derived bioenergy as a practical and urgent route to sustainable energy security in light of growing worries about global warming and depleting fossil fuel supplies.

Protecting energy resources and increasing access to clean, dependable energy are also essential tactics for reducing poverty globally. Microalgal biomass is now the most promising renewable resource that has the potential to replace the use and reliance on fossil fuels. A wide range of biofuels, including such as bio-gas, bio-oil, bio-methane, bio-hydrogen, and bioethanol, may be produced from this biomass and have the potential to drastically alter the world's energy supply.

Bio-oil

Bio-oil, sometimes referred to as bio-crude or pyrolysis oil, is made through a thermochemical conversion process that uses high temperatures and an oxygen-free atmosphere to convert biomass into liquid oil, carbonaceous particles, and gaseous byproducts. Bio-oils can be used as partial or renewable replacements for traditional petroleum oils, despite certain similarities between the two. The two methods are thermochemical liquefaction and pyrolysis main processes used to produce bio-oil.

Bio-oil, which includes a complex combination of organic molecules originating from the biomass's lipids, proteins, and carbohydrates, is produced in far greater quantities than algal lipids. Some microalgal species play a significant role in the production of bio-oil worldwide; for example, *Spirulina* may contribute up to 41%, *Scenedesmus* can contribute between 24% and 45%, *Dunaliella* around 37%, and *Desmosomes* can provide yields of up to 49%.^[32]

Bio-hydrogen

The variety of biofuel sources is still a major energy concern, and the generation of bio-hydrogen has attracted a lot of attention lately. Despite its promise, low biomass concentrations and expensive production techniques currently restrict the practical use of large-scale bio-hydrogen generation.^[24] It has been demonstrated that a variety of biological stresses, including light deprivation in some algae species, may significantly increase the generation of hydrogen gas. However, as this technology is still in its infancy, more research and development might lead to improvements in its scalability and optimization in the future.

Biogas

Although the use of microalgal biomass presents a number of difficulties, it offers a possible substitute for terrestrial crops in the generation of biogas. Algae have significantly improved the production efficiency of biogas when combined with traditional feedstocks. Algal-derived glucose and glycine were thermochemically treated in neutral, acidic, and alkaline environments to examine the thermal breakdown routes and the possibility of simultaneous bio-hydrogen and

Table 1: Stages of microalgae biotechnological applications across different sectors

Sector	First Stage	Second Stage	Third Stage
Bioenergy	Bioprospecting of biofuels	Optimization of the production process	Use of biocatalysts or development of new routes for biofuel production
Health care, therapeutics	Bioprospecting of healthcare compounds	Recombinant protein technology	Clinical assays for biomedical purposes
Environment	Biodegradation and biotransformation assays	Selection of phytoremediation or wastewater treatment processes	On-site applications with integrated process development
Aquaculture	Selection of strains and evaluation for specific fish or crustacean aquaculture	Balanced diet design	Feed additive production and implementation in aquaculture farms
Cosmetics	Bioprospecting of natural products from microalgae	Skin applications	Medical care supplements for skin applications
Foods	Natural products	Probiotics	Food supplements

bio-methane fermentation. With studies looking at a variety of substrates, such as algae, wood, grasses, and solid waste, algal biomass has become a promising feedstock for the production of bio-methane. Although algae often produce more biomass than terrestrial plants, their cultivation is frequently limited by a number of nutritional inadequacies that can restrict development and the potential for total bio-methane generation.^[33]

Bioethanol

Because of algae's higher biomass yields, species variety, diverse biochemical composition, and improved photosynthetic efficiency, there has been a lot of interest in producing bioethanol from algal biomass. Algae are a unique feedstock for the production of bioethanol because of their high concentration of carbs and polysaccharides as well as their comparatively thin cellulose cell walls. Particularly in microalgae, polysaccharides such as cellulose and starch are major sources of carbohydrates. These polysaccharides may accumulate significantly due to the intricate multilayered structure of microalgal cell walls, which makes them ideal for fermentation procedures that produce bioethanol.^[34]

Because of their high carbohydrate content and simplicity of culture, brown algae are a popular feedstock for the production of ethanol among several species of algae. Furthermore, it has been shown that acid hydrolysis of red algal agar may transform polysaccharides into fermentable sugars; yet, actual ethanol yields are still quite modest, even if the theoretical maximum yield is almost 45%. The fermentation of one kilogram of dried seaweed usually produces 0.08–0.12 kilos of ethanol, depending on the kind of algae and the particular pre-treatment and hydrolysis techniques used.^[35] Notably, bioethanol made from algae overcomes a number of significant drawbacks of both first-generation and

second-generation bioethanol, which are made from food crops such as maize, rice, or sugarcane.

Biodiesel

The choice of feedstock has a significant impact on the cost of producing biodiesel, which accounts for between 50% and 85% of the entire fuel price. A careful evaluation of the feedstock's efficiency, purity, and possibility for by-product valorization is necessary to produce biodiesel at a reasonable cost. A key component of this effort is transesterification, a chemical process that turns lipids, mainly triacylglycerols and free fatty acids, into non-toxic and ecologically beneficial biodiesel.^[36]

This technique produces fatty acid alkyl esters with much lower molecular weights from high-viscosity crude algal oil. For example, transesterification is the process of reacting crude oil with an alcohol, usually methanol, while a catalyst is present. The result is methyl esters of fatty acids, or biodiesel, and glycerol, which is a useful byproduct. Because of their remarkably high lipid content, *C. vulgaris* and *Chlorella protothecoides* are two microalgal species that have been thoroughly studied for the manufacture of biodiesel. Unsaturated fatty acids are the main component of microalgal biodiesel. In addition, the distinct algal populations seen in algal biomass recovered from wastewater systems provide a range of fatty acid profiles that can affect the quality and properties of biodiesel.

Phase of development for applications of microalgal biotechnology^[37]

The various industries that benefit from microalgal biotechnology are listed in Table 1. These industries include

aquaculture, the production of bioenergy, healthcare through the use of bioactive phenolic compounds, environmental applications like CO₂ sequestration and sustainable waste valorization, and as sources of balanced feed ingredients. Recent research indicates that the mix of microalgal biomass, which includes proteins, lipids, ash, amino acids, and carbohydrates, gives cosmetic compositions crucial functional qualities including stiffness, moisture retention, durability, and skin protection.

Based on the maturity of application domains, the development of microalgal biotechnology may be roughly divided into three successive stages. Early-phase research and development are the main emphasis of the first stage, which usually lasts 2–5 years. Intermediate developments are represented by the second stage, which lasts around 3–5 years. The attainment of technological competence and preparedness for extensive industrial application define the last stage, which lasts for at least 7 years.^[38] By keeping an eye on developments and advancements in the corresponding application fields, the shift between these phases is assessed.

CONCLUSION

Microalgal biotechnology's advancement has been accelerated by the wide range of useful compounds that may be extracted from algal biomass. Microalgal biomass has emerged as a possible solution to these urgent global issues in the face of an increasingly unpredictable future characterized by impending food and energy shortages as well as the intensifying effects of climate change. A varied class of photosynthetic microorganisms and microalgae is essential for removing CO₂ from the atmosphere and regenerating oxygen. In regulated conditions, they may produce a range of beneficial secondary metabolites while also assimilating a variety of contaminants to power their metabolic processes. A wide range of bioproducts, such as medications, cosmeceuticals, cosmetics, functional foods, antimicrobial agents, and aquaculture feed additives, has been produced using microalgae as living bioreactors. In addition, a lot of research is being done to optimize microalgal systems for the production of sustainable bioenergy. In addition to these uses, several microalgal-based technologies are being investigated for their possible contributions to biodegradation, bioconversion, bioremediation, COVID-19 treatment approaches, and the reduction of other environmental contaminants.

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