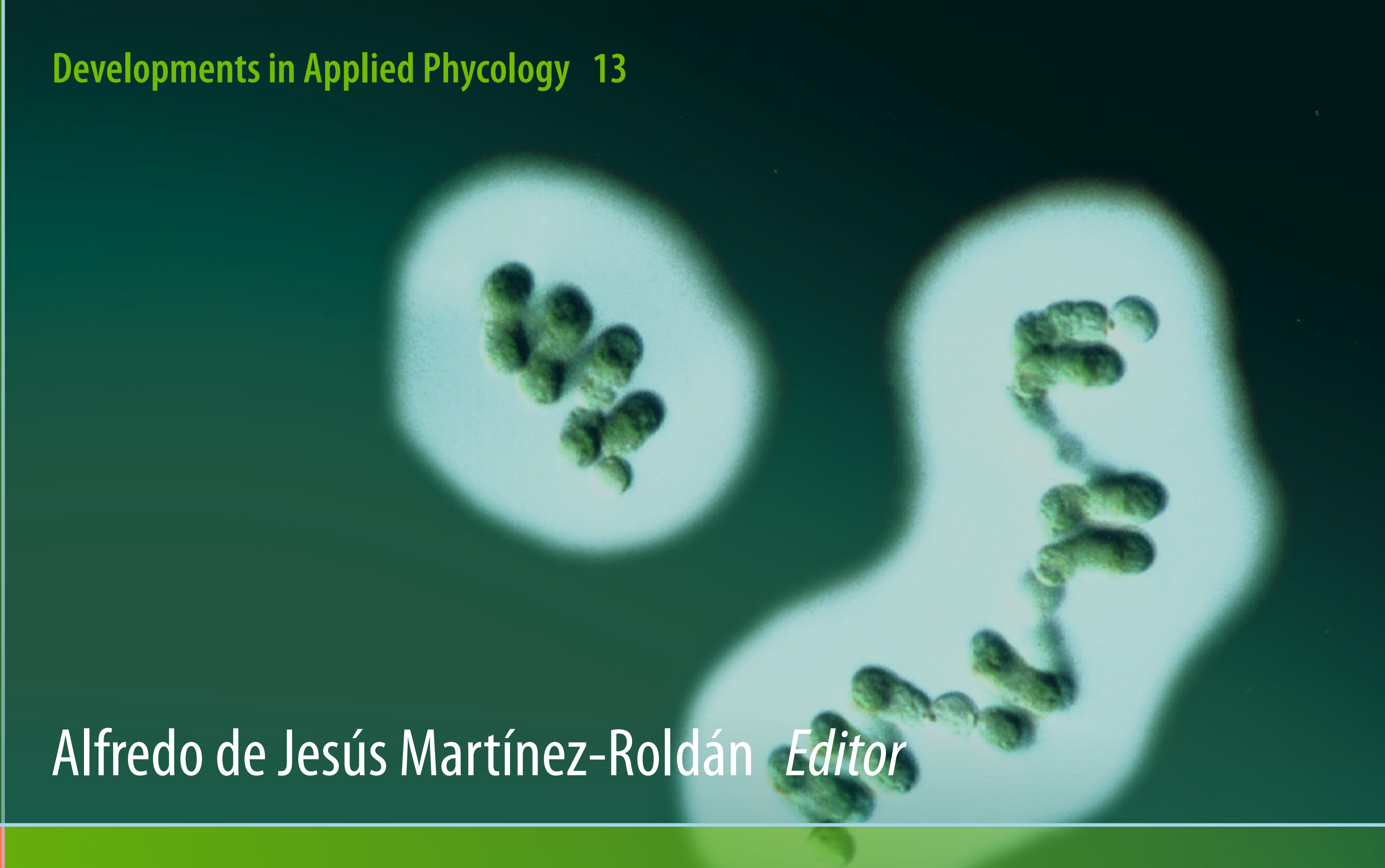
Developments in Applied Phycology 13



Alfredo de Jesús Martínez-Roldán *Editor*

Biotechnological Processes for Green Energy, and High Value Bioproducts by Microalgae, and Cyanobacteria Cultures

Springer

Developments in Applied Phycology

Volume 13

Series Editor

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Aims and Scope

Applied Phycology, the practical use of algae, encompasses a diverse range of fields including algal culture and seaweed farming, the use of algae to produce commercial products such as hydrocolloids, carotenoids and pharmaceuticals, algae as biofertilizers and soil conditioners, the application of algae in wastewater treatment, renewable energy production, algae as environmental indicators, environmental bioremediation and the management of algal blooms. The commercial production of seaweeds and microalgae and products derived there from is a large and well established industry and new algal species, products and processes are being continuously developed.

The aim of this book series, Developments in Applied Phycology, is to present state-of-the-art syntheses of research and development in the field. Volumes of the series will consist of reference books, subject-specific monographs, peer reviewed contributions from conferences, comprehensive evaluations of large-scale projects, and other book-length contributions to the science and practice of applied phycology.

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To Sofía, María Paula, Arya, and Jorge

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Thanks to all those who at some point arrived and remained, to those who arrived and left, and to all those who will arrive.

Gracias a todos aquellos que en algún momento llegaron y permanecen, a los que llegaron y se marcharon y a todos aquellos que llegarán

Contents

Introduction to Environment-Friendly Bioprocesses by Microalgae and Cyanobacteria

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Alfredo de Jesús Martínez-Roldán

Abstract

Microalgae include diverse organisms with different cellular structures (prokaryotic and eukaryotic), the capability to grow in diverse ecosystems (sea, rivers, lakes, lagoons, soil, etc.), and the possibility of performing autotrophic, mixotrophic, and heterotrophic metabolism. This diversity is the reason for their ability to produce and accumulate different compounds, many of which have the potential to be used in industrial processes. These compounds include lipids, proteins, amino acids, carotenoids, biofuels, adsorbents (carbons), polyunsaturated fatty acids, and animal feeds. In addition, processes based on microalgae can capture carbon dioxide (CO_2), eliminate pollutants (such as nitrogen, phosphorous, and heavy metals), or even utilize biomass as feed for livestock. Nevertheless, the growth conditions, induction process, and extraction and purification strategies are specific to every strain. This book aims to include recent developments in environment-friendly processes derived from microalgae and cyanobacteria.

Keywords

Microalgae · Cyanobacteria · High-value bioproducts · Biotechnology

1.1 Introduction

Microalgae are photosynthetic microorganisms with many metabolic pathways very similar to superior plants; nevertheless, they have several advantages compared with terrestrial plants, such as the possibility to be cultivated and reaching massive cultures in photobioreactors and the fact that the development of fruits, seeds, or a specific tissue is not necessary, as in the case of vegetable crops, to obtain a high-value product (Barsanti and Gualtieri 2014). Historically, microalgae have been used in experimental studies to elucidate metabolic pathways, specifically for the description of oxygenic photosynthesis. The experiments performed to describe the route of carbon fixation in oxygenic photosynthesis, commonly known as the Calvin–Benson–Bassham cycle, were developed using *Chlorella* cultures exposed to light for small periods and subsequently inactivated by dropping in hot methanol. This experiment allowed us to determine all the molecules produced in the Calvin–Benson cycle and describe all the chemical reactions involved (Biel and Fomina 2015).

Since then, microalgae and cyanobacteria have been proposed to develop diverse bioprocesses with two main objectives: eliminating different pollutants from liquid and gaseous effluents and producing high-value products by taking advantage of specific metabolic pathways (Borowitzka 2013). Recently, genetic modifications of microalgae and cyanobacteria were carried out to either increase the amount of a specific metabolite or improve the performance of the culture under special operational conditions (Barati et al. 2021; Beacham et al. 2017).

Around the 1950s, the majority of the research related to microalgae and cyanobacteria focused on their role in the facultative lagoon and the tertiary treatment of wastewaters, as symbiosis was observed between aerobic bacteria and photosynthetic microorganisms and an increase in the efficiency of organic matter removal was observed in the presence of microalgae (Oswald et al. 1957; Oswald and Golueke 1960; Oswald and Gotaas 1957).

Later, the development of technological devices for microalgal culture started; their containers were called photobioreactors and today their variety is huge (Martínez-Roldán and Cañizares-Villanueva 2015). Some photobioreactors include configurations, such as fermenters,

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tubular horizontal and/or vertical airlift mixing, columns, flat panels, and thin layers, all of which satisfy specific culturing requirements of the microorganisms, such as mixing, shear stress, and light supply. In all configurations, the main objective is to maximize biomass production, biomass productivity, or even the production of a specific metabolite or a high-value product (Acién et al. 2017; Chini Zittelli et al. 2013; Torzillo and Chini Zittelli 2015). Recently, microalgal biotechnology has focused on environmental applications or the production of high-value bioproducts, but always from a sustainability perspective.

Some environmental applications take advantage of the diverse qualities of microalgal cultures, e.g., their capability to fix carbon dioxide (CO_2), which is useful for the developing processes to capture CO_2 or to reduce the CO_2 concentration in fuel gases from diverse industrial processes. However, there are no technological developments at the commercial scale, because there are numerous obstacles related to the engendering of the process (Solovchenko and Khozin-Goldberg 2013; Wang et al. 2008; Zhou et al. 2017). Another characteristic used for environmental applications of microalgae is the fast consumption of nutrients from its culture media (nitrogen and phosphorus), which has been fully studied, allowing us to describe the role of microalgae and cyanobacteria in the stabilization of lagoons or even the use of microalgal cultures for the tertiary treatment of domestic wastewater. The inclusion of microalgae and cyanobacteria in wastewater treatment permits the elimination of nitrogen and phosphorus, which cannot be eliminated by aerobic and anaerobic processes for organic matter elimination (Martínez-Roldán and Ibarra-Berumen 2019; Olguin 2003).

With regard to the use of microalgae and cyanobacteria in wastewater treatment, the proposal is to eliminate specific contaminants from water, some of which are heavy metals and semimetals. Microalgal biomass has a huge potential for the removal of ions because it is possible to use both live and dead biomass as adsorbents. The use and process of microalgal biomass as ion adsorbents is very efficient, and recovery of the removed ions is quite simple (Cañizares-Villanueva 2000; Perales-Vela et al. 2006). Owing to their capability to remove pollutants from the culture medium, the microalgae are proposed to eliminate specific pollutants recently detected in urban wastewaters and denominated as emerging contaminants; the major problem with this type of compound is its wide variety because the sources are very diverse (Peña-Guzmán et al. 2019).

Some emerging pollutants have actually reached high concentrations and are further increasing, causing concern to the scientific community. Therefore, many studies have focused on the development of processes to eliminate them. The emerging contaminants include colorants, drugs, hormones, healthcare products, cosmetics, and antibiotics. Microalgae have proven to eliminate the contaminants by the process of adsorption/absorption or even biotransformation; however, in this case, it is possible to obtain subproducts with higher toxicity than the original ones (Geissen et al. 2015; Jain et al. 2022; Keen et al. 2014; Peña-Guzmán et al. 2019). Therefore, regardless of the potential of microalgae and cyanobacteria to eliminate these contaminants, there are no commercial-scale treatment processes, and there is an unknown economic cost and real efficiency.

The potential environmental application of microalgae is not only the elimination of pollutants from liquid and gaseous effluents. Since the biomass is a source of a large number of different molecules, several of them have high market value (Borowitzka 2013). Some of these bioproducts include pigments, antioxidants, fatty acids, oils, polyunsaturated fatty acids, and the lipid fraction of the biomass, which can be converted into liquid fuels, such as biodiesel or jet fuel (Cañizares-Villanueva et al. 2022).

The high-value bioproducts are very diverse, but some of them have higher potential for pigment production because there are strains with the capability to produce high amounts of different carotenoids or xanthophylls, such as beta-carotene, astaxanthin, lutein, violaxanthin, and antheraxanthin, as well as many other molecules with similar chemical properties. In addition, it is possible to obtain molecules with antioxidant properties, such as polyphenols, tocopherols, and ascorbic acid (Safafar et al. 2015). The lipid fraction of the biomass can be used to obtain a specific fatty acid (oleic, linoleic, arachidonic, etc.), or subjected to a chemical process to obtain a specific type of fuel, such as biodiesel or jet fuel (Rodolfi et al. 2009). Nevertheless, the number of processes at the production scale is small, and economic feasibility has not been proven.

There are many possible applications of microalgae and cyanobacteria, but it is necessary to develop processes from the perspective of sustainability. This has led to an increase in the proposal of processes based on the use of wastewater as a nutrient source and the complete exploitation of the biomass in the biorefinery concept (because of its similarity with oil refinery). The biorefinery processes propose to reduce the effect of the processes on the environment and reduce the generation of residues and reach a positive life-cycle assessment.

This book analyzes many examples of biotechnological applications of microalgae and cyanobacteria cultures, some of them with experimental data, and other chapters that include reviews with a general overview of innovative and promising applications.

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CO_2 Bio-capture by Microalgae and Cyanobacteria Cultures

2

Cigdem Demirkaya and Hector De la Hoz Siegler

Abstract

Climate change is a global problem caused by the rise of carbon dioxide (CO_2) concentration in the atmosphere. To limit global warming to less than 2 °C, large-scale deployment of technologies to remove CO_2 from the air will be needed. As highly efficient, photosynthetic, single-cell factories, microalgae and cyanobacteria can play a critical role among carbon-negative technologies. Bio-capture of CO_2 using photosynthetic microbes is a viable method for recycling CO_2 into biomass, which can subsequently be utilized to produce bioenergy, fertilizers, biomaterials, and other high-value products. This chapter provides an overview of the different strategies for utilizing microalgae and cyanobacteria for CO_2 capture directly from the atmosphere or stationary point sources with minimal environmental impacts. Challenges, research needs, and opportunities for the integration of CO_2 bio-capture within a biorefinery perspective are discussed.

Keywords

Carbon capture · Microalgae · Cyanobacteria · Photosynthesis · Bioconversion · Biorefinery · Climate change

2.1 Introduction

Due to the role of carbon dioxide (CO_2) in driving global climate change, there is an increasing global pressure to limit CO_2 emissions, particularly at large-emission source points. In 2015, with the signing of the Paris Agreement, nations committed to reduce global emissions annually by 3% to avoid a global climate catastrophe. However, this has not been achieved and the path that is being followed, which includes mainly treatment of point sources, such as flue gas, is not enough to meet the target of limiting global average temperature below a 2 °C increase. Thus, there is a rising urgency for innovative methods to mitigate new emissions and to remove the CO_2 already in the atmosphere.

Photosynthetic microbes, including microalgae, cyanobacteria, and diatoms have a great potential for mitigating and abating CO_2 emissions, while producing valuable products (Moreira and Pires 2016; Vale et al. 2020) and fostering a more sustainable bio-economy. If part of the CO_2 captured in the biomass is used to make products with relatively long life (i.e., years), or if they are permanently stored, then the cultivation of microalgae and cyanobacteria can become a key carbon-negative technology to address the climate change crisis.

Biological carbon capture is an effective and simple approach with potentially much lower energy needs compared to physical and chemical carbon capture methods. For instance, the standard technology for carbon capture in post-combustion processes is amine scrubbing, using primary or secondary amines. This technology is the basis of several megaton-scale carbon-capture projects (Feron et al. 2020). The regeneration of the amine, however, is very energy-intensive, introducing a significant energy penalty and reducing the overall mitigation potential of this method (Alesi and Kitchin 2012; Stern et al. 2013).

Photosynthesis is nature's carbon capture solution. Photosynthetic organisms utilize the energy from light to drive the reaction of CO_2 and water and form biomolecules. In this way, carbon is removed from the atmosphere and stored in biomass. Gross primary production (GPP) refers to the amount of CO_2 removed from the atmosphere by photosynthesis. This is known to be one of the main fluxes controlling the carbon balance in the atmosphere and has a significant potential to offset anthropogenic carbon emissions (Beer et al. 2010). Terrestrial GPP is estimated at about 120 Pg of carbon per year (Beer et al. 2010), while marine phytoplankton are estimated to account for an additional 50 Pg of carbon per year (Yang et al. 2020). Global anthropogenic energy-

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related CO_2 emissions in 2020 were estimated at 8.6 Pg of Carbon (IEA 2021), or roughly 5% of the carbon naturally fixed by photosynthesis. Thus, it is conceivable that technological solutions based on photosynthesis will be able to offset anthropogenic carbon emissions.

Microalgae and cyanobacteria are rapidly growing microorganisms able to fix CO_2 with efficiency 10 to 50 times higher than that of terrestrial plants (Cheah et al. 2015; Raheem et al. 2018; Zhang and Liu 2021); they have high areal productivity, and high lipid and/or carbohydrate content. They are able to grow in nonarable land, with minimal nutrient inputs, and in wastewater, saline, brines, or halo-alkaline waters (Moreira and Pires 2016). Thanks to their high areal productivity and ability to grow in hostile environments, photosynthetic microbes are more suitable for biological carbon capture technologies than terrestrial plants. The use of dedicated crops for industrial purposes has previously resulting in the diversion of arable lands away from traditional food crops, creating unintended impacts on food cost and supply, resulting in the well-known food versus fuel dilemma (Darnoko and Cheryan 2000; Issariyakul and Dalai 2012). This dilemma is avoided when using photosynthetic microbes.

In addition to their role of fixing CO_2 emissions, microalgae and cyanobacteria can be used to remove nitrogen and phosphorous from agricultural and industrial effluents, reducing eutrophication of receiving water bodies (Fal et al. 2021; Guo et al. 2018; W. Zhang et al. 2020). The microbial biomass produced can be used for several applications including the production of biofuels, bioplastics, food supplements, animal feed, cosmetic additives, pharmaceutical products, and building materials (Venkata Mohan et al. 2016; Singh and Dhar 2019; Daneshvar et al. 2022). Thus, biological carbon capture with microalgae and cyanobacteria offers a wide range of opportunities for building sustainable integrated processes to support a bioresource-based circular economy (Venkata Mohan et al. 2016; Hemalatha et al. 2019; Vale et al. 2020).

This chapter presents an overview of the factors affecting the performance of carbon capture using photosynthetic microorganisms and the different strategies for utilizing microalgae and cyanobacteria for CO_2 capture directly from the atmosphere or stationary point sources with minimal environmental impacts. The challenges, research needs, and opportunities for the integration of CO_2 bio-capture from a biorefinery perspective are discussed.

2.2 Photosynthesis: Natural Carbon Capture

Photosynthesis is a natural way of capturing CO_2 and is the process responsible for transforming Earth's atmosphere from CO_2-rich, more than 2 billion years ago when CO_2 atmospheric concentration was about 10 to 200 times the present level, to a relatively CO_2-depleted one (Kaufman and Xiao 2003). Photosynthesis is carried out in two phases, see Fig. 2.1. In the first phase, light-dependent reactions capture light energy and convert it into chemical energy that is ultimately stored within nicotinamide adenine dinucleotide phosphate (NADPH) and adenosine triphosphate (ATP). The light reactions occur in the photosynthetic unit (PSU), a light-harvesting complex and reaction center located within the thylakoid membrane. The NADPH and ATP energetic molecules are then consumed in the second phase, where light-independent reactions are used to convert CO_2 into sugars (Barsanti and Gualtieri 2005; Jensen et al. 2017; Sánchez-Baracaldo and Cardona 2020).

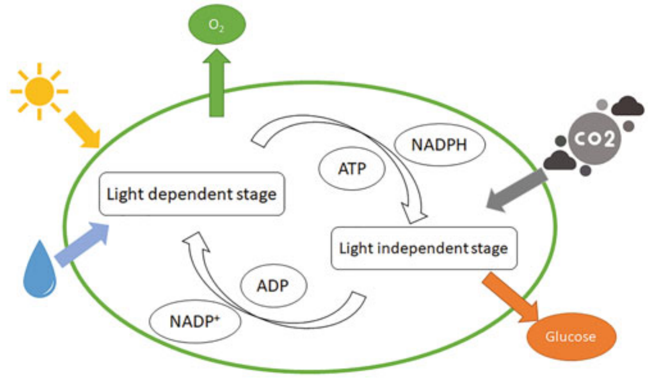

Fig. 2.1 Light-dependent and light-independent stage during photosynthesis (Adapted from Cheah et al. 2015)

$$2NADP + 2H_2O + 2ADP + 2P_i \longrightarrow 2NADPH_2 + 2ATP + O_2 \text{ Light} - \text{dependent reaction}$$

$$CO_2 + 4H^+ + 4e^- \longrightarrow CH_2O + H_2O \text{ Light} - \text{independent reaction}$$

Although photosynthesis originated in an environment with much higher CO_2 concentrations, microalgae and cyanobacteria cells have developed biological adaptations to survive under low CO_2 concentrations. The carbon concentrating mechanism (CCM) allows to increase the concentration of CO_2 within the cells relative to the normal CO_2 concentration in the air (300–400 ppm). The CCM improves photosynthetic efficiency by increasing the available CO_2 for ribulose bisphosphate carboxylase-oxygenase (RuBisCO). RuBisCO is an important enzyme that converts CO_2 into organic carbon (Gruber and Feiz 2018). Another important enzyme in the CCM is carbonic anhydrase (CA), which catalyzes the reversible conversion of CO_2 into HCO_3^- (DiMario et al. 2018).

Several different CCMs have been identified in microalgae and cyanobacteria. In cyanobacteria, there are two types of carboxysomes (α-type and β-type), which are specialized compartments for the accumulation of HCO_3^-. The accumulated HCO_3^- is then converted into CO_2 by the action of carboxysomal CA (Moroney and Ynalvez 2007). In the case of microalgae, *Chlamydomonas reinhardtii* has been studied as the model organism to understand the action of the CCM. In this microalga, the CCM can be divided into two phases. In the first phase, inorganic carbon is gathered from the environment in the form of CO_2 and HCO_3^- by transporter proteins. In the second phase, as the concentration of HCO_3^- increases in the chloroplast, HCO_3^- is converted into CO_2 by the action of CA (Wang et al. 2015).

Although microalgae and cyanobacteria have in general faster growth rate and higher light conversion efficiency than plants, the efficiency of large cultivation is hindered by the low CO_2 gas–liquid mass transfer rate and reduced light penetration and shading. In a fast-growing culture, the CO_2 transfer rate between the gas phase (i.e., air above culture or bubbles sparged) and the liquid medium phase media is too low to compensate for the CO_2 uptake by the cells (Zuccaro et al. 2020), resulting in carbon limitation and slower photosynthetic rate.

Light limitation also affects photosynthetic efficiency negatively (Brennan and Owende 2010). Although theoretical photosynthetic efficiency ranges between 8% and 12%, practical photosynthesis efficiency is rarely above 1.5–2%. This efficiency loss is primarily caused by light scattering and nonproductive absorption, which causes light to be exponentially attenuated as it travels along the optical path (Nwoba et al. 2019). During photosynthesis, the PSU can be in either a resting or nonactivated state or an activated state. A resting PSU is activated by the absorption of a photon. The absorption of excess photons converts functional PSUs into nonfunctional PSUs, resulting in photoinhibition (Camacho-Rubio et al. 2003). In a culture, the cells closer to the light source are more prone to experience photoinhibition as they are exposed to a higher light intensity, while the cells further down the optical path may not receive enough light. Thus, overall photosynthetic efficiency is affected by both light attenuation and scattering and photoinhibition.

2.3 CO_2 Bio-capture from Different Sources

Microalgae and cyanobacteria can capture CO_2 from stationary point emission sources, such as power plants or other carbon-intensive industrial processes, or directly from the atmosphere. The CO_2 concentration in the atmosphere is 0.03–0.06% (v/v), while for stationary point sources the CO_2 concentration can vary between 6 and 15% (v/v) (Rahaman et al. 2011). The cost and energy needed for capturing CO_2 is inversely proportional to concentration, the lower the concentration of CO_2 in a given source, the more expensive the capture process. Thus, capture from large-point sources is one of the best and more efficient options to abate CO_2 emissions, as the effluent streams from combustion and industrial processes have higher CO_2 concentrations.

Figure 2.2 shows how different CO_2 sources can be integrated with microalgae and cyanobacteria biomass cultivation for CO_2 bio-capture. The following sections present an overview of technologies for CO_2 bio-capture and a discussion of the efficiency of these bio-capture methods.

2.3.1 Bio-capture of CO_2 from Stationary Point Sources

Flue or stack gases released by various stationary point sources, such as industrial complexes and power plants, have relatively high CO_2 concentrations ranging from 6 to 15% (v/v) (Thomas et al. 2016). These flue gases can be used to boost the productivity of microalgal and cyanobacteria cultures. The high concentration of CO_2 in the flue gas allows for a faster mass transfer rate, higher photosynthetic efficiency, and support a higher final cell density in the cultures.

Because of the low CO_2 solubility, the flue gas needs to be injected or bubbled directly into the cultivation medium, adding to electricity demands. The energy spent in bubbling and mixing the CO_2 in the media represents up to 27% of the overall production cost; at the same time, typically between 55 and 90% of the CO_2 injected in the culture is lost to the atmosphere (Markou et al. 2014; Caia et al. 2018). Consequently, significant research efforts have been dedicated to

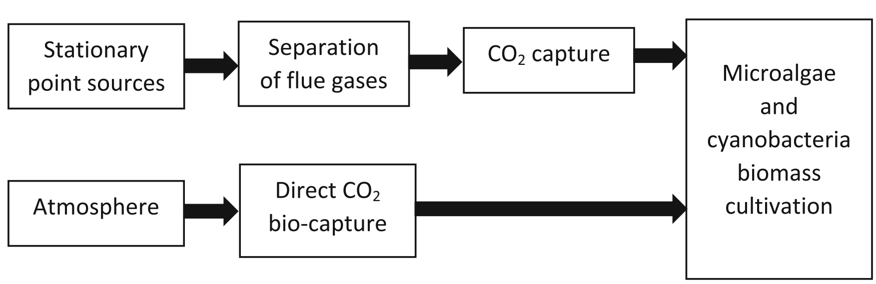

Fig. 2.2 CO_2 bio-capture from different sources and utilization in biomass

improving CO_2 diffusion rates (see Sect. 2.5) and increasing CO_2 utilization efficiency.

Microalgae and cyanobacteria strains with high CO_2 uptake rate and high biomass productivity are desirable to ensure an efficiency CO_2 capture process. Sepulveda et al. (2019) assessed the ability of 11 different microalgae and cyanobacteria strains to capture CO_2 and produce high biomass productivity. They reported that *Scenedesmus almeriensis* and *Neochloris oleoabundans* were the most productive strains when used in CO_2 capture processes compared to the cyanobacteria strains. Park et al. (2021) investigated CO_2 fixation at a CO_2 concentration ranging from 5 to 40% from biogas in five pure microalgal cultures and a mixed microalgal culture, including *Chlorella sp., Anabaena variabilis, Chlamydomonas iyengarii, Chlorella vulgaris,* and *Chlorella sorokiniana*. The highest CO_2 fixation rate was reported for *Chlorella sp.* at 1.785 g $L^{-1}d^{-1}$ at a CO_2 concentration of 15%. Additional studies on CO_2 capture and uptake by microalgae and cyanobacteria are summarized in Table 2.1.

Although the high CO_2 level in flue gas is beneficial for microalgae and cyanobacteria growth, these gases usually contain substances that can be inhibitory (Lam et al. 2012; Vale et al. 2020). In particular, unfiltered flue gas from coal combustion can have high concentration of SO_x and NO_x, microparticles, and heavy metals, such as mercury, which can present a challenge to biomass growth (Napan et al. 2015; Thomas et al. 2016). As the concentration of SO_x and NO_x increases, the acidity of the culture medium increases and this lowers the pH (Vale et al. 2020). Low pH values may inhibit microalgal growth or even result in cell death. Duarte et al. (2016) evaluated the tolerance of microalgae and cyanobacteria to the presence of NO_x and SO_x and found that strains were able to tolerate those gases at concentration of up to 400 ppm. Aslam et al. (2017) demonstrated the adaptation of mixed microalgal communities to growth in unfiltered flue gas from coal combustion. This microalgal community was dominated by *Desmodesmus* spp., which was the most resilient species. Radmann et al. (2011) evaluated the NO_x and SO_x tolerance of *C. vulgaris,*

Table 2.1 Application of microalgae in CO_2 capture from the atmosphere and CO_2 reach sources

CO_2 source	Microorganism	CO_2% (v/v)	CO_2 fixation rate (g L^{-1} d^{-1})	Culture conditions	Reference
Atmospheric CO_2	*Chlorella vulgaris* and *Pseudokirchneriella subcapitata*	Air	0.305	OECD medium, $T = 22$ °C, different dark/light cycles at 126 μmol photons m^{-2} s^{-1}	Pires et al. (2014)
	Dunaliella tertiolecta	0.04	0.07	Artificial sea water, $T = 26$ °C, continuous illumination at 350 μmol photons m^{-2} s^{-1}	Hulatt and Thomas (2011)
	C. vulgaris	0.09	3.45	Artificial sea water, $T = 25$ °C, continuous illumination at ~50 μmol photons m^{-2} s^{-1}	Fan et al. (2008)
	Anabaena sp.	0.03	1.45	Allen and Arnon medium, $T = 23$ °C, light/dark cycles with 900 μmol photons m^{-2} s^{-1}	Ramkrishnan et al. (2014)
Enriched CO_2 supply	*Spirulina* sp. DUT001	2	1.0	Zarrouk medium, $T = 25$ °C, photoperiod = 12:12, 188.7 μmol photons m^{-2} s^{-1}	Zhu et al. (2020)
	Chlorella vulgaris	15	1.0	BBM medium, $T = 28$ °C, membrane PBR, photoperiod = 12:12, 120 μmol photons m^{-2} s^{-1}	Senatore et al. (2021)
	Chlorella vulgaris, Synechocystis salina, Microcystis aeruginosa,	5	0.101	OECD test medium, $T = 24$ °C, continuous illumination at 120 μmol photons m^{-2} s^{-1}	Gonçalves et al. (2014)
	Scenedesmus obliquus	12	22.8	Soil extract medium, $T = 26$ °C, outdoor airlift PBR, 220–240 μmol photons m^{-2} s^{-1}	Li et al. (2011)
	Chlorella vulgaris	5–25	0.27–0.47	ESP-31 medium, $T = 28$ °C, continuous illumination at 50 μmol photons m^{-2} s^{-1}	Chou et al. (2019)
	Microalgae consortia	5.5	0.09–0.12	BBM medium, $T = 30$ °C, photoperiod = 12:12 at 1650.3 μmol photon m^{-2} s^{-1}	Aslam et al. (2018)
	Scenedesmus almeriensis, Neochloris oleoabundans	Flue gas	2.8–2.64	Natural water from the river Seine and the artificial Seine river water, $T = 25$ °C, continuous illumination at 390 μmol photons m^{-2} s^{-1}	Sepulveda et al. (2019)
	Spirulina sp.	2	0.81	Modified Zarrouk medium, $T = 20$ °C, pH 9, continuous illumination at 188.7 μmol photons m^{-2} s^{-1}	Zhu et al. (2020)
	Chlorella sp	15	1.785	BG-11 medium, pH 8.2–8.7, $T = 25$ °C, photoperiod = 12:12 at 171.91 μmol photon m^{-2} s^{-1}	Park et al. (2021)

Scenedesmus obliquus, and *Synechococcus nidulans* by using a simulated gas from coal combustion, containing 12% (v/v) CO_2, 100 ppm NO_x, and 60 ppm SO_x. They reported that the growth of *C. vulgaris* and *S. obliquus* was not inhibited, but this was not the case for *S. nidulans.*

In short, stationary point sources are excellent for supplying the required CO_2 concentration for carbon capture and biomass production in microalgae and cyanobacteria. However, direct use of flue gas is not, in general, possible without any separation or treatment. Identifying robust microalgae and cyanobacteria strains capable of high CO_2 bio-capture and adapted to the high concentration of other gases present in flue gas should be further explored to maximize the CO_2 bio-capture potential of microalgae and cyanobacteria culture. Furthermore, despite the large energy requirements for supplying CO_2 to the cultivation medium, a significant amount of the CO_2 provided is released into the atmosphere, decreasing net capture, and incurring inefficient energy use. Thus, additional research efforts must be directed at improving CO_2 diffusion rates and integrating different CO_2 capture techniques with microalgae and cyanobacteria cultures.

2.3.2 Biological Direct Air Capture with Microalgae and Cyanobacteria

Although capture from concentrated large-point sources of CO_2 is the most desirable and efficient option, about half of CO_2 emissions are from diffuse sources (Moreira and Pires 2016). Moreover, the CO_2 already accumulated in the atmosphere will continue to negatively contribute to climate change (Keith 2009). Thus, capture of atmospheric CO_2 using negative emissions technologies is needed to address emissions from diffuse sources and to restore the carbon balance in the atmosphere. Direct air capture (DAC) refers to technologies that directly remove CO_2 from the atmosphere. These technologies also offer the advantage of deployment in any location, independent of a specific source and without added costs for CO_2 transportation.

In the case of microalgal and cyanobacterial cultures, to capture 1 million ton of CO_2 per year, between 70 and 86 km^2 of the culture is needed, assuming an average productivity of 20 g m^{-2} day^{-1} of dry weight biomass and considering that about 1.6 to 2 grams of CO_2 are captured for every gram of biomass (Sayre 2010). Given the large land requirements for cultivation, it is more likely to find suitable land for deployment of large-scale cultures far away from industrial areas or population centers, where land may be scarce or expensive.

The low concentration of CO_2 in the atmosphere, however, is a major drawback as it limits CO_2 solubility and mass transfer rate into the cultivation media (Kumar et al. 2010). Carbon utilization has been shown to be more efficient when the supply rate of CO_2 matches closely with the demand of the growing biomass (Sobczuk et al. 2000; Vale et al. 2020). For DAC, active bubbling is not desirable as it requires a high energy input and will increase water evaporation. For a cost and energy-effective carbon capture process, the CO_2 supply to the cultivation needs to be improved by passive means.

To compensate for the low solubility of CO_2 in natural waters, several microalgae and cyanobacteria strains rely on the CCM to increase the intracellular concentration of bicarbonate ions and use CA to convert the HCO_3^- back to CO_2 to be used in photosynthesis. The ability of some microalgae and cyanobacteria to utilize HCO_3^- have prompted several researchers to explore the use of alkaline culture conditions to enhance CO_2 mass transfer rate and total inorganic carbon concentration in the culture media (Chi et al. 2013; Canon-Rubio et al. 2016). Alkalinity is defined as the sum of the concentration of hydroxyl ions, bicarbonate ions, and carbonates ions, times the corresponding ion charge. As alkalinity increases, so does the concentration of dissolved inorganic carbon. High alkalinity also improves CO_2 mass transfer rate from the gas phase to the cultivation medium, as there is an increased driving force (Vadlamani et al. 2019). In addition, it provides a higher buffering capacity enabling the uncoupling of CO_2 absorption from biomass growth (Chi et al. 2013; Santos et al. 2013), as illustrated in Fig. 2.3.

Because alkalinity can inhibit cell growth, it is necessary to operate at relatively low alkalinity or use alkali-tolerant or alkaliphilic microalgae or cyanobacteria strains. Extreme alkaline conditions together with alkaliphilic microalgae and cyanobacteria have been suggested for large-scale cultivation (Piiparinen et al. 2018; Song et al. 2019; Zhu et al. 2020). In soda lakes, at pH > 10, high concentrations of bicarbonate are present supporting a high growth rate of CO_2 fixation by photosynthetic microbes, while the consumed CO_2 is spontaneously replenished by passive diffusion from the air above the lakes (Sharp et al. 2017).

Vadlamani et al. (2017) demonstrated high biomass productivity by cultivating *C. sorokiniana* (>16 g $m^{-2}\cdot d^{-1}$) in a 4.2 m^2 raceway pond using an alkaline cultivation medium and atmospheric CO_2 alone. In another study, Zhu et al. (2020) used extreme alkaline conditions with pH ranging between 10.0 and 12.5 for DAC using *Spirulina* sp. DUT001. Effective CO_2 bio-capture was reported with maximum biomass productivity about 1.00 g $L^{-1}d^{-1}$ and carbon-capture rate of 0.81 g L^{-1} d^{-1}.

2.4 Integrated Biorefinery for a Carbon-Neutral Circular Bioeconomy

To foster the development of an integrated, sustainable, and robust biological CO_2 capture process, circular economy principles must be applied to ensure the efficient processing

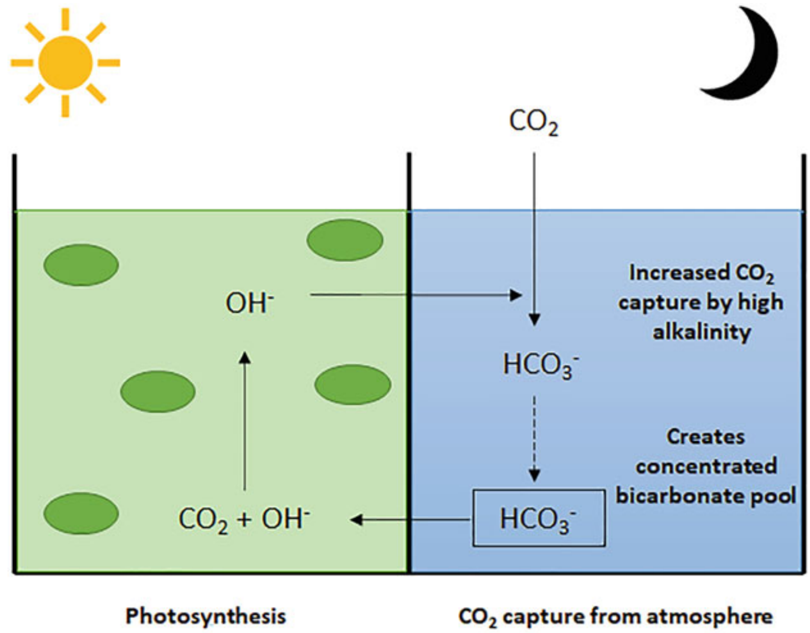

Fig. 2.3 Mechanism of the bicarbonate pool's role in the efficient capture of CO_2 from the air and rapid carbon supply for photosynthesis (Adapted from Zhu et al. 2020)

and conversion of the generated biomass, while designing out or minimizing waste, maximizing the reutilization of resources, and regenerating natural systems. The microalgal or cyanobacterial biomass produced from the CO_2 capture process consists of several biochemical compounds, including lipids, proteins, polysaccharides, and pigments. These compounds can be extracted and converted into biobased products which, in turn, displace alternative products obtained from non-sustainable sources or that have a high carbon footprint (Daneshvar et al. 2022).

An integrated biorefinery can be conceived where bio-capture of CO_2 occurs simultaneously with the production of valuable products, thus converting waste CO_2 emissions into carbon-neutral products. As microalgae or cyanobacteria require several nutrients for growth, the biorefinery concept starts with cultivation using a nutrient-rich waste stream, such as wastewater, as the primary source of nitrogen, phosphorus, sulfur, and trace metals; thus, allowing the recycling and reclamation of these materials and reducing nutrient supply costs (Razzak et al. 2013; Whitton et al. 2015; Yen et al. 2015; Singh et al. 2016).

Conventional downstream processing involves harvesting and separating biomass from the cultivation media, followed by biomass pretreatment by homogenization, beading, and chemical hydrolysis to extract products of interest, and finish with the upgrading to the final products (Khoo et al. 2020). This traditional downstream processing approach is wasteful and expensive. Thus, in the biorefinery approach, the goal is to utilize the biomass to generate multiple products within a single process.

The approach in microalgal biorefineries is the cascade system (Francavilla et al. 2015; Hemalatha et al. 2019), which allows for different biomass fractions to be extracted either simultaneously or separately by different methods (Monlau et al. 2021). Selecting the most suitable downstream processing strategy depends on the nature of the bioproducts, the required energy, and technology availability (Bastiaens et al. 2017). The use of mild separation technologies, which require low pressure, less energy, and less chemicals, is preferred for downstream to increase energy efficiency and avoid damaging the most sensitive products, which are often the most valuable. Figure 2.4 presents a possible pathway to produce multiple products from microalgal and cyanobacterial biomass.

Carbajal Tejada et al. (2020) studied five different biorefinery scenarios using *Scenedesmus dimorphus* biomass as feedstock to produce biodiesel, dihydroxyacetone, fishmeal, glycerol, and vegetable oil. Their results showed that integrated reactive distillation with the biological oxidation of glycerol to produce dihydroxyacetone was the most efficient biorefinery scenario. In another study, Moncada et al. (2014) simulated two different integrated biorefineries using *Chlorella* sp. grown with a CO_2-rich stream and sugar cane to determine the most promising scenario. The use of *Chlorella* sp. biomass to produce biodiesel, glycerol, ethanol, sugar, and electricity was found more environmentally and economically viable option than just using sugarcane alone.

Microalgal and cyanobacterial biomass is mainly composed of lipids (7–60%), proteins (6–71%), and carbohydrates (5–60%), depending upon the species and culture conditions (García-Garibay et al. 2003; Chen et al. 2013; Aziz et al. 2020). These macromolecules can be converted into several different products. The most effective use of the produced biomass will be the one that displaces

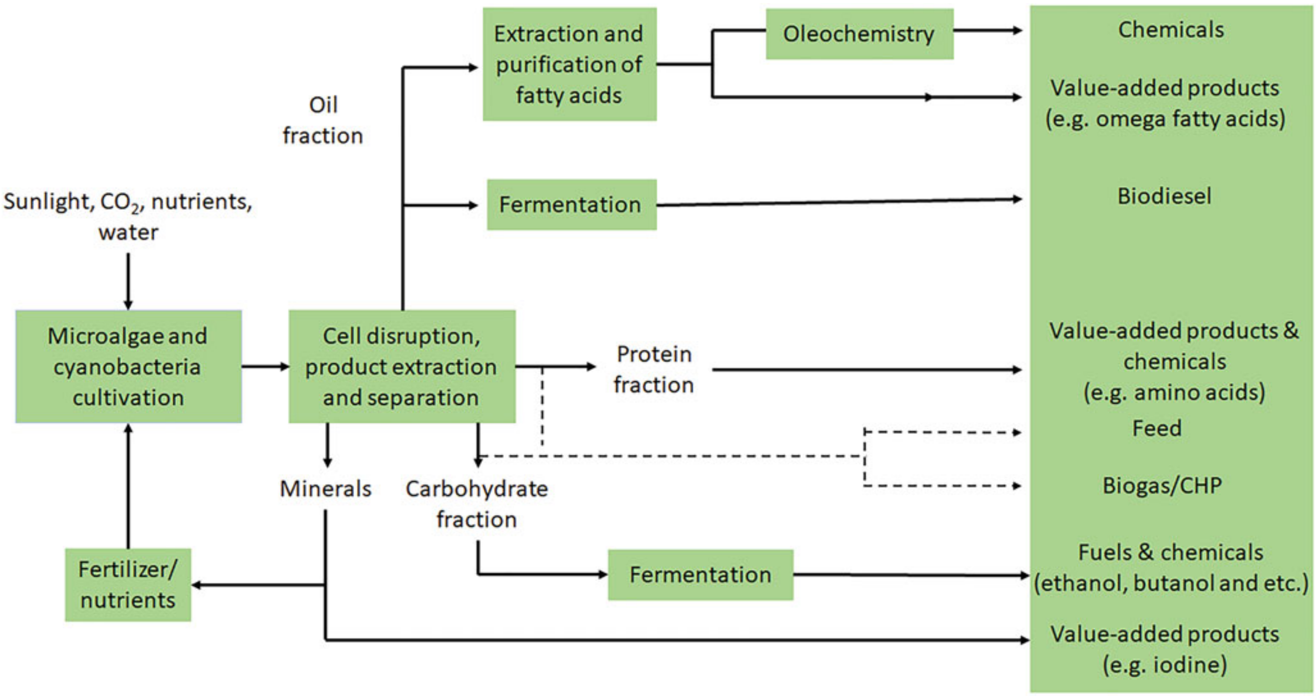

Fig. 2.4 Application of different downstream processing methods for integrated biorefinery (Adapted from Chew et al. 2017)

unsustainable feedstock or existing products with a high carbon footprint. In the following subsections, we discuss some of the products that can be more directly targeted as they either have a high carbon footprint or are high value, and therefore can help to improve the economics of the bio-capture process.

2.4.1 Biofuels

The high lipid content (15–60%) in many microalgae makes them very attractive for biodiesel production (Converti et al. 2009; Yeh and Chang 2011; Moazami et al. 2012; Polat and Altınbaş 2020). Lipid content can be further increased by manipulating several cultivation parameters (Huang and Su 2014); Polat and Altınbaş 2020). Although biodiesel production from microalgae is quite advantageous, it has not yet been commercially deployed due to the high energy-intensive downstream processing methods.

The carbohydrates in microalgal and cyanobacterial biomass are a suitable feedstock for hydrogen, bioethanol, and biogas production by fermentative pathways (Ho et al. 2013; Lakatos et al. 2019; Nagappan et al. 2019). Microalgal and cyanobacterial biomasses do not contain rigid cell wall components such as lignin, which makes them easier to process. Biodiesel production can be integrated with fermentation and anaerobic digestion to simultaneously produce a variety of energy products (Harun et al. 2011; González-González et al. 2018). After extraction of lipids for biodiesel production, the rest of the biomass, including carbohydrates, can be used as a feedstock for hydrothermal liquefaction, fermentation, or anaerobic digestion to produce biodiesel, bioethanol and/or biogas respectively. A recent technoeconomic analysis has shown that when microalgal biofuel production was integrated with other processes to obtain multiple valuable products (polyhydroxy butyrate and astaxanthin), the biofuel price was reduced to a competitive value of \$0.54/L (Rafa et al. 2021).

2.4.2 Bioactive Compounds

The main bioactive compounds produced by microalgae include polyunsaturated fatty acids (PUFAs), carotenoids, chlorophylls, phycobiliproteins, polysaccharides, and proteins.

Several microalgae produce PUFAs with known bioactive properties, such as eicosapentaenoic acid (EPA, C20:5 ω−3), docosahexaenoic acid (DHA, C22:6 ω−3), arachidonic acid (ARA, 20:6 ω−6), and γ-linolenic acid (GLA, 18:3 ω−6) (López et al. 2019). Many of these fatty acids have been studied for their anti-inflammatory activity and have been shown to prevent many diseases such as asthma, diabetes, and cardiovascular diseases (Cheng et al. 2018; Hess et al. 2018).

Some microalgal polysaccharides are considered biologically active molecules with promising applications in food, cosmetic additives, and pharmaceutical products (De Jesus

Raposo et al. 2013; Barkia et al. 2019; Gouda et al. 2022). Sulfated polysaccharides are prominent for having antioxidant, anti-inflammatory, antitumoral, antiviral, antibacterial, and immunomodulatory activities (De Jesus Raposo et al. 2013). Among these, sulfated polysaccharides extracted from *Porphyridium* sp. and *Nannochloropsis oculata* have been shown to have antiviral, antitumoral, and immunostimulatory properties in pharmaceutical and therapeutic applications (Custódio et al. 2015; Casas-Arrojo et al. 2021). Apart from these benefits, polysaccharides obtained from microalgae are used as stabilizers, thickening agents, emulsifiers, and lubricants in foods, cosmetics, and textiles (Costa et al. 2021). Because some of these polysaccharides are released into the growth media during cultivation, their recovery and purification is much simpler than in the case of intracellular compounds.

Microalgae and cyanobacteria also produce essential amino acids, peptides, and proteins (Amorim et al. 2020). These valuable compounds have found multiple applications in the pharmaceutical, cosmetic, and food industries (Costa et al. 2021). *Spirulina platensis* and *C. vulgaris* are known for their high protein contents of 46–71% (Lupatini et al. 2017; Tokuşoglu and Ünal 2003). They have been used as food and feed supplements for decades, as they contain several essential amino acids, such as threonine, methionine, isoleucine, valine, leucine, lysine, and histidine (Wang et al. 2021). Montalvo et al. (2019) reported antioxidant, chelating, antimicrobial, anti-inflammatory, and anti-collagenase activity of three biopeptide fractions from *Arthrospira maxima* OF15 for potential applications in the pharmaceutical, cosmetic, and food industries.

Although all these metabolites have various applications, there are several limitations to be addressed. The main problem is the high cost of cultivation and extraction. Applying the biorefinery concept to obtain more than one product is essential to reach a cost-effective production system (Balasubramaniam et al. 2021).

2.4.3 Pigments

The three main pigment classes obtained from microalgal and cyanobacterial biomass include chlorophylls, carotenoids, and phycobilins (Koyande et al. 2019). These pigments are mainly utilized as food and feed supplements, food coloring, and as pharmaceutical and cosmetic additives because of their high antioxidant action (Begum et al. 2016; Morocho-Jácome et al. 2020). β-carotene produced by microalgae can be used as a food colorant, food and feed additive, or as precursor for vitamin A, and antioxidants (Wolf et al. 2021). Lutein and zeaxanthin are other carotenoids that are produced by microalgae and cyanobacteria and have been used as food additives due to their antioxidant activities (Granado-Lorencio et al. 2009). Phycocyanin is a blue-colored pigment-protein complex that is extracted from cyanobacteria species such as *Arthrospira platensis* (Zeng et al. 2012). It has antioxidant, anticancer, and anti-inflammatory properties and helps to improve immune function and inhibit cancer cell growth (Zeng et al. 2012). It has been used as a food ingredient and as an additional supplement to fight or prevent cancer. Furthermore, due to its naturally blue color, it has been used as a colorant for the textile and food industries to replace synthetic colorants (Rahman et al. 2017).

Pigments are one the most valuable products that can be obtained from microalgae. Although market size and product price are higher than other products, pigment extraction methods are expensive and involve the use of toxic materials. Economic feasibility and sustainability need to be improved by, e.g., investigating more environmentally friendly and non-toxic extraction methods (Rajesh et al. 2020).

2.4.4 Plastics

The global demand for plastics has increased exponentially since large-scale production of plastics started in the 1950s (Geyer et al. 2017). The carbon footprint of plastic production was estimated at 1.7 Gigaton (Gt) CO_2 equivalent in 2015 (Cabernard et al. 2021), representing 4.5% of global greenhouse gas (GHG) emissions. Because many plastics have long life spans, with some taking tens to hundreds of years to decompose, replacing fossil fuel–derived plastics with microalgal plastics is a feasible strategy for long-term carbon sequestration.

Some microalgae and cyanobacteria species produce metabolites that can be used directly for the fabrication of bioplastics, such as polyhydroxyalkanoates (PHAs) (Balaji et al. 2013), while other plastics can be obtained by chemical routes using the lipid, protein, and carbohydrate fraction of the microalgal and cyanobacterial biomass. Plastics obtained from microalgae and cyanobacteria can be designed to have properties comparable to those of fossil fuel–derived plastics (Rahman and Miller 2017).

Polyhydroxybutyrate (PHB), a type of PHA, is frequently found in cyanobacteria as an energy and carbon storage compound. Several cyanobacteria, such as *Synechocystis*, *Synochoccocus*, *Nostoc*, and *Spirulina*, are known PHB producers (Yashavanth et al. 2021), while *Synechocystis* PCC6803 has been used as a model organism to study the production of PHB (Singh et al. 2019; Koch et al. 2020). PHB is a biodegradable alternative to thermoplastics, such as polyethylene and polypropylene, and it is being commercially produced for applications in disposable food ware (McAdam et al. 2020). Recent studies have focused on the use of genetic engineering to increase PHB yield and integrate cultivation system with wastewater to reduce cultivation cost (Larkum et al. 2012; Katayama et al. 2018; López Rocha et al. 2020; Chong et al. 2021).

The triglycerides accumulated by many microalgae can be used as feedstock for the synthesis of different polyols, by chemically attaching hydroxyl groups to the unsaturated bonds in the fatty acid chains. These polyols can be converted into polyurethanes for a variety of applications by means of epoxidation and ring-opening by methanol, ethylene glycol, or lactic acid; hydroformylation; or urethane reaction with isocyanates (Hai et al. 2020; Peyrton et al. 2020). Another attractive material that can be derived from microalgae is acrylonitrile, which is a monomer widely used in the production of a variety of plastics, rubbers, resins, acrylic fibers, and polyacrylonitrile (PAN) carbon fibers (Karp et al. 2017). Glycerol obtained from the transesterification of algal oils can be converted into acrylonitrile by direct ammoxidation in the gas phase (Guerrero-Pérez and Bañares 2008).

2.4.5 Oleochemicals

Although the lipids in microalgae are thought of mainly as precursors for biofuel production, they can also be used as feedstock to produce many oleochemicals. Oleochemicals are products derived from triglycerides, including fatty acids, fatty alcohols, methyl esters, and glycerin with a wide range of applications, from food and cosmetic additives to drilling fluids and lubricants. Most oleochemicals are derived from palm, soya, canola, coconut, and palm kernel oils (Parsons et al. 2020). The sustainability of the oleochemical industry, especially palm oil, has been the source of growing public concern due to its many negative environmental impacts (Rival and Levang 2014). Although biobased, the oleochemical industry has an elevated carbon footprint and its expansion through land-use conversion has resulted in permanent damage to the biodiversity of sensitive ecosystems along with the release of massive amounts of GHG (Parsons et al. 2020). Palm-driven land-use change in Southeast Asia emits nearly 0.5 Gt of CO_2 equivalent each year, roughly 1.4% of global net GHG emissions, and is responsible for extensive ecosystem degradation. The use of algal-derived lipids to produce oleochemicals will allow phasing out unsustainable feedstock.

2.5 Challenges and Recent Progress

The main challenge for scaling up CO_2 bio-capture using microalgal and cyanobacterial cultures is the low CO_2 diffusion rates from the gas phase into the liquid culture medium, which translates into reduced CO_2 capture efficiency (Lam et al. 2012; Yen et al. 2015). To enhance the CO_2 absorption and mass transfer some approaches have been suggested, such as improving the existing photobioreactors (PBR), designing new PBR systems, and evaluating the influence of several parameters (temperature, pH, mixing, culture type, culture density, and CO_2 concentration) in the CO_2 diffusion (Morales et al. 2018).

2.5.1 PBR Design

Microalgal and cyanobacteria cultivation can be done in open ponds or closed PBRs. Open ponds are low in capital and operating costs, which is beneficial for scaling up the production; however, biomass productivity is lower than in closed systems due to high CO_2 losses, evaporation, uncontrolled climate conditions, and contamination risk (Acién et al. 2017). On the other hand, closed systems provide a better-controlled environment and prevent CO_2 and evaporation losses, allowing to reach higher biomass productivity (Acién et al. 2017). The existing PBRs designs for CO_2 bio-capture and biomass cultivation are vertical column reactors (bubble columns or airlift), tubular reactors, flat-plate reactors, and stirrer tank reactors.

A key limiting factor in CO_2 bio-capture is the low photosynthetic conversion efficiency. Although PBRs are designed to provide a better light path than what is achieved in open ponds, light conversion efficiency is much lower than what can be theoretically achieved. Implementing new strategies to improve light penetration and delivery directly to cells minimizes energy losses and maximizes productivity. Light penetration can be increased by changing PBR orientation (horizontal, vertical, or tilted), using solar tracking devices to change the direction of the light coming to the PBR surface (Castrillo et al. 2018), optimizing light intensity and spectral distribution to prevent photoinhibition from excess light (Ooms et al. 2016), and maintaining heterogeneous light distribution to eliminate dark zones (Nwoba et al. 2019; De la Hoz Siegler 2022).

Several studies optimizing microalgae and cyanobacteria cultivation have focused on improving CO_2 gas–liquid mass transfer by improving reactor configurations to increase the contact between the gas and liquid phases. The initial bubble size is known to affect CO_2 mass transfer rate, with a smaller initial bubble size ($R = 0.98$ mm) resulting in increased CO_2 fixation. Hence, a small bubble is more suitable to be supplied in PBRs for the purpose of high CO_2 fixation (Barahoei et al. 2020). However, producing micro- or nanobubbles is a high energy-consuming process in which high-pressure devices are needed. Besides, high shear stress that is generated because of the bursting of small bubbles is damaging to algal cells.

Xu et al. (2020) developed a spiral-ascending CO_2 dissolver to enhance the CO_2 dissolution rate and prolong gas–

liquid contact time to improve microalgal growth in a horizontal tubular PBR. This cost-efficient and effective CO_2 dissolver reduced the bubble generation diameter by 23.4% and increased the CO_2 mass transfer rate by 69.2%. In another study, Gonçalves et al. (2021) designed an Oscillatory Flow Reactor with Smooth Periodic Constrictions (OFR-SPC) to improve CO_2 mass transfer without compromising fluid turbulence, which can negatively impact the most sensitive cells. This system promoted high gas–liquid mass transfer rates with low power consumption and controlled fluid turbulence. Therefore, it can be a promising technology to be used in microalgal cultivation, replacing the commonly used bubble-column and airlift PBRs.

2.5.2 Cultivation Parameters

The efficiency of the biological CO_2 capture process is also affected by CO_2 concentration, temperature, and pH. Temperature affects the solubility of CO_2 as well as the specific growth rates. CO_2 solubility decreases as temperature increases. Thus, to improve the solubility of CO_2, the culture medium must be maintained at cooler temperatures. Each microorganism has its own optimal growth temperature, with thermophilic strains typically having higher specific growth rate than mesophilic or psychrophilic organisms. For CO_2 bio-capture from stationary point sources, thermophilic microalgal and cyanobacterial strains can be used to tolerate the high temperature of flue gas without causing a decrease in cell growth. Varshney et al. (2018) reported isolation of two novel green algal strains, *Asterarcys quadricellulare* and *C. sorokiniana*, from water bodies that were near a steel plant in India. These strains had high specific growth rates of up to 0.06 h^{-1} and 0.1 h^{-1}, respectively. Furthermore, they were able to tolerate high temperatures up to 43 °C and high concentration of CO_2 and NO_x. In addition, they reported that when they eliminated NO coming from the flue gas, strains were able to accumulate lipids up to 44% to 46% of dry biomass. The tolerance for high temperature and CO_2 concentration and their ability to accumulate lipid make these strains very attractive for CO_2 bio-capture applications.

The pH of the culture media also has a direct impact on the dissolution of CO_2 and other inorganic molecules, as it affects the chemical equilibrium between HCO_3^- and CO_3^{2-}, precipitation of phosphates, volatilization of ammonia, and the solubility of trace elements. Moreover, it directly affects cell growth due to its effect on the activity of different enzymes. For many microalgae and cyanobacteria strains, the optimum pH value is between 7 and 9. However, some organisms are known to thrive in extreme conditions. For instance, *Spirulina* grows optimally in highly alkaline conditions (pH 9–11). Alkaline conditions, at pH above 11.0, can reduce the contamination risk from grazers, protozoa, and other competing algae. As discussed in Sect. 2.3.2, it also increases the CO_2 mass transfer rate and total dissolved inorganic carbon concentration.

Mixing is another key cultivation parameter that affects the gas–liquid mass transfer in PBRs. Poor mixing can cause dead areas that lack nutrients and CO_2, thus reducing overall reactor productivity. Increasing mixing rates through mechanical agitation or aeration can improve the CO_2 mass transfer, but it results in higher power consumption and introduce excessive shear stress and cellular damage.

2.5.3 Future Direction and Opportunities

Carbon capture technologies based on microalgae and cyanobacteria cultures are promising for a carbon-neutral future. However, for successful implementation of this technology, innovation in culture strategies, integration with other processes, and process optimization are needed.

Integration of other CO_2 capture processes with microalgae and cyanobacteria cultures can increase overall CO_2 capture and recovery. Chemical absorption technologies are based on the ability of different solvents, such as ionic liquids and alkaline solutions, to react with CO_2 (Vega et al. 2020). The successful integration of chemical absorption of CO_2 with *Spirulina* cultivation was demonstrated by De Rosa et al. (2015). Membrane separation uses a CO_2 permeable membrane to allow the CO_2 to pass through, while preventing other flue gasses from reaching the culture media. In this way, inhibition of the cell by toxic gasses is avoided (Cheng et al. 2021).

Recent studies have focused on the identification of highly efficient microalgae and cyanobacteria strains and on enhancing the efficiency of CO_2-fixing enzymes through genetic engineering (Barati et al. 2021). Increased CO_2 assimilation and biomass growth were reported by construction of new NADPH consumption pathways (Zhou et al. 2016), while the photosynthetic efficiency of *Nannochloropsis* sp. was improved by overexpression of RuBisCO activase (Wei et al. 2017). These achievements, however, need to be demonstrated at larger scale to ensure that the genetic constructs are stable over long cultivation periods.

2.6 Conclusion

Biological capture of CO_2 is a promising approach to mitigate CO_2 emissions and remove excess carbon from the atmosphere. Large-scale cultivation of microalgae and cyanobacteria provides environmental benefits with the possibility of producing a wide portfolio of valuable products for further a more sustainable and circular bioeconomy.

Although significant progress in bio-capture of CO_2 by microalgae and cyanobacteria has been achieved, additional research efforts are needed to improve CO_2 capture efficiency.

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