



Microalgae as a key tool in achieving carbon neutrality for bioproduct production

Assemgul K. Sadvakasova^a, Bekzhan D. Kossalbayev^{a,b}, Meruyert O. Bauenova^a,
Huma Balouch^a, Yoong Kit Leong^{c,d}, Bolatkhan K. Zayadan^a, Zhiyong Huang^{e,f},
Hesham F. Alharby^g, Tatsuya Tomo^h, Jo-Shu Chang^{c,d,i,j,*}, Suleyman I. Allakhverdiev^{k,l,m,**}

^a Faculty of Biology and Biotechnology, Al-Farabi Kazakh National University, Al-Farabi 71, Almaty 050038, Kazakhstan

^b Department of Chemical and Biochemical Engineering, Institute of Geology and Oil-Gas Business Institute Named after K. Turyssov, Satbayev University, Almaty 050043, Kazakhstan

^c Department of Chemical and Materials Engineering, Tunghai University, Taichung 407, Taiwan

^d Research Center for Smart Sustainable Circular Economy, Tunghai University, Taichung 407, Taiwan

^e Tianjin Key Laboratory for Industrial Biological Systems and Bioprocessing Engineering, Tianjin Institute of Industrial Biotechnology, Chinese Academy of Sciences, Tianjin 300308, China

^f National Technology Innovation Center of Synthetic Biology, Tianjin 300308, China

^g Department of Biological Sciences, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia

^h Department of Physics, Graduate School of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan

ⁱ Department of Chemical Engineering, National Cheng Kung University, Tainan 701, Taiwan

^j Department of Chemical Engineering and Materials Science, Yuan Ze University, Chung-Li 32003, Taiwan

^k K.A. Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, Botanicheskaya Street 35, Moscow 127276, Russia

^l Department of Plant Physiology, Faculty of Biology, M.V. Lomonosov Moscow State University, Leninskie Gory 1-12, Moscow 119991, Russia

^m Faculty of Engineering and Natural Sciences, Bahcesehir University, Istanbul, Turkey

ARTICLE INFO

Keywords:

Microalgae
CO₂ emissions
Carbon neutrality
Decarbonization
Bioenergy
Bioproducts

ABSTRACT

The upcoming global climate change as a result of anthropogenic action is now increasingly attracting the attention of scientific communities. Over the past three decades, researchers and industries around the world have spent a lot of time and effort developing various carbon capture and storage technologies, which, despite their promise, are still economically complex, with unclear long-term consequences to the environment. As an alternative, biological carbon sequestration is considered an attractive method of atmospheric CO₂ fixation with the production of biomass, which, in turn, can be used as a readily renewable feedstock for the production of biofuels and other valuable products. This review focuses on the latest data of microalgae research in terms of key carbon footprint minimization strategies, which include features of the carbon concentrating mechanism (CCM) in microalgae, the main range of biofuels and the possibility of obtaining valuable metabolites based on them, such as bioplastics, biofertilizers, and biologically active compounds.

Abbreviations: BACs, biologically active compounds; Bio-H₂, biohydrogen; CA, carbonic anhydrase; Cars, carotenoids; CCM, carbon concentrating mechanism; CCUS, carbon capture, utilization, and storage; CH₄, methane; Chls, chlorophylls; CO, carbon monoxide; CO₂, carbon dioxide; COD, chemical oxygen demand; DW, dry weight; FAs, fatty acids; FW, fresh weight; GHG, greenhouse gas; GHGs, greenhouse gases; HDPE, high-density polyethylene; HRAP, high-rate algae pond; IAA, indole-3-acetic acid; IBA, indole-3-butanoic acid; LDPE, low-density polyethylene; MDH, malate dehydrogenase; ME, malic enzyme; O₂, oxygen; OUC, ornithine-urea cycle; PBPs, phycobiliproteins; PEPC, phosphoenolpyruvate carboxylase; PHA, polyhydroxyalkanoates; PP, polypropylene; PVC, polyvinyl chloride; TAG, triacylglyceride.

* Correspondence to: J.-S. Chang, Department of Chemical and Materials Engineering, Tunghai University, Taichung 407, Taiwan.

** Correspondence to: S. I. Allakhverdiev, K.A. Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, Botanicheskaya Street 35, Moscow 127276, Russia.

E-mail addresses: changjs@mail.ncku.edu.tw (J.-S. Chang), suleyman.allakhverdiev@gmail.com (S.I. Allakhverdiev).

<https://doi.org/10.1016/j.algal.2023.103096>

Received 7 December 2022; Received in revised form 26 February 2023; Accepted 5 April 2023

Available online 10 April 2023

2211-9264/© 2023 Elsevier B.V. All rights reserved.

1. Introduction

The widespread use of fossil fuels and active anthropogenic activities contributing to the increase of greenhouse gases (GHGs) level in the

atmosphere has become the primary causes of global climate change in recent decades. Carbon dioxide (CO_2) is the primary GHG accounting for roughly 60 % of total global emissions [1,2]. Despite a temporary decrease during the COVID-19 pandemic, its concentration in the

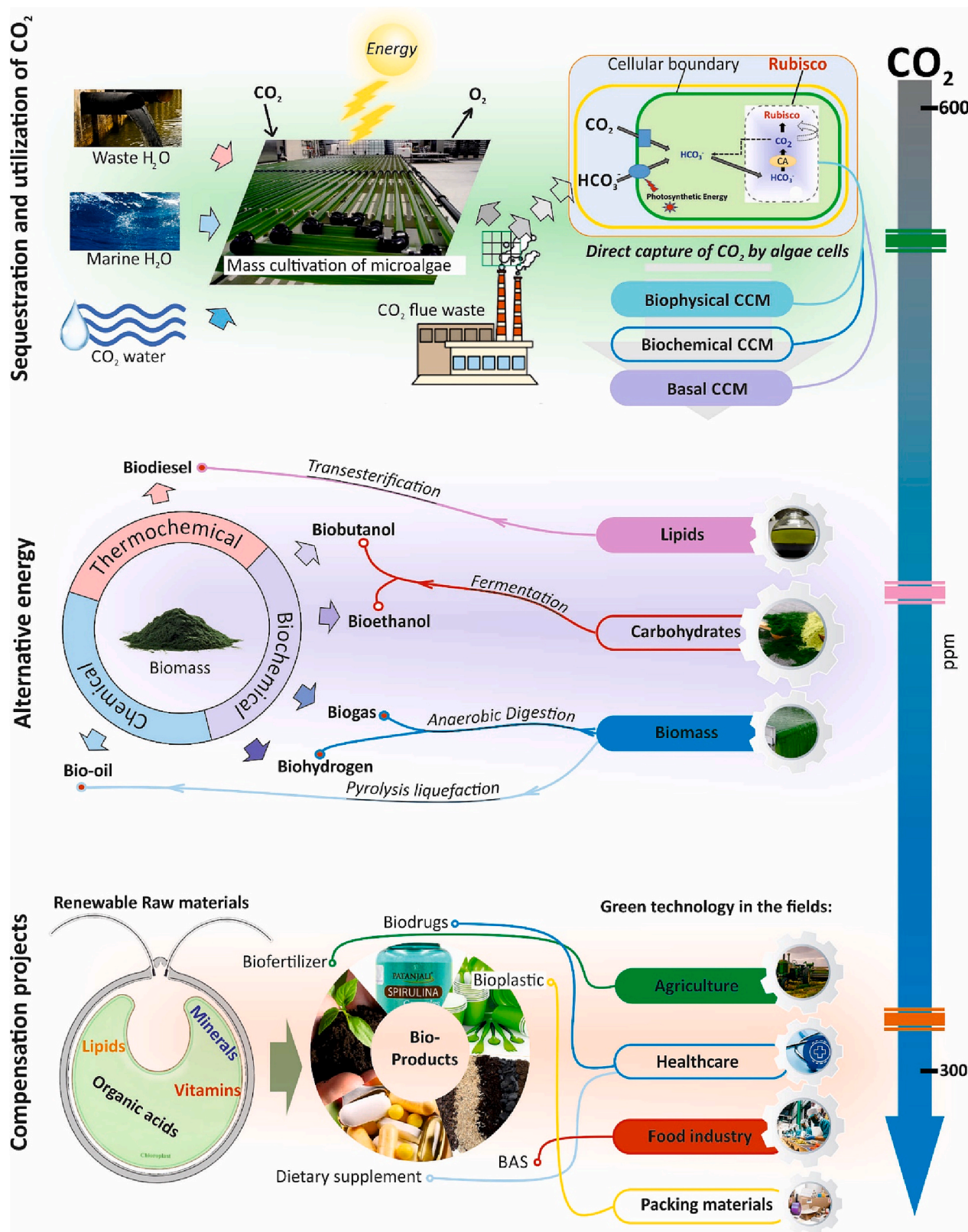


Fig. 1. Key strategies and potential of microalgae in carbon sequestration and bioconversion to achieve carbon neutrality. Abbreviation: CCM – CO_2 concentrating mechanisms.

atmosphere has risen to approximately 400 ppm and is continue to rise [3].

To combat global warming, the entire world community has set a difficult goal of reaching carbon neutrality by 2050 [4,5]. The strategy's main approaches can be boiled down into three main aspects: CO₂ emissions can be reduced by cleaning the air, switching to alternative energy sources, and investing in relevant projects [6,7]. The approaches outlined above should include new innovative technologies such as biotechnologies to harness the potential of the planet's bioresources. Microalgae are fast-growing, photosynthetic aquatic organisms with a wide metabolic potential that makes them ideal for these carbon neutrality strategies. Furthermore, unlike embryophytes, they lack lignin, and photosynthetically sequestered carbon can be easily recycled back into food webs [8]. Photosynthesis is one of the most natural and sustainable methods of capturing and storing CO₂ from the atmosphere. Microalgae can photosynthetically capture about 100 Gt of CO₂ per year and convert it into useful biomass [7]. Moreover, over the last three decades, researches on microalgal biotechnology have intensively focused on exploring their potential for bioenergy production [9]. Numerous scientists have identified their immense potential in the production of a variety of liquid and gaseous biofuels [5]. Another important aspect is the development of "green" technologies, where microalgae are considered as a valuable resource for the production of many valuable bio-products in a natural way and contribute to the development of various offset projects that help reduce CO₂ emissions into the atmosphere. The fundamental modification of hazardous industries and their replacement with harmless ones using natural, low-carbon technologies for the production of valuable natural chemical compounds, including food additives, biofertilizers and bioplastics, is certainly aimed at reducing the amount of CO₂ produced [10,11].

There are several reports in the literature about the assimilation of CO₂ by various microorganisms, focusing on the CO₂ fixation metabolic pathway [12,13], and the potential of phototrophic microorganisms for biofuel production is also being actively investigated [14]. Nevertheless, in this manuscript, the most recent research on microalgae is thoroughly examined in relation to the three aspects of achieving carbon neutrality outlined above. First, recent data on carbon dioxide sequestration by microalgal cells are summarised and examined, as well as alternative techniques of biological CO₂ sequestration. The manuscript then highlights the primary range of phototrophic microorganism-based biofuels, their challenges, and future possibilities in bioenergy. Finally, the manuscript analyses the potential of microalgae in the development of projects to gain additional products such as bioplastics, biofertilizers, and biologically active additives, the production of which also contributes to lowering CO₂ emissions. We also discuss the challenges and opportunities for developing bioconversion of captured carbon dioxide into biofuels and other valuable products.

It is expected that the information contained in this review will provide a thorough understanding of how algae can represent a high-tech, low-cost and environmentally friendly solution to many of the current needs of our society, while achieving carbon neutrality and thus contributing to the creation and development of a bioeconomy based on algae (Fig. 1).

2. Microalgae as carbon dioxide capture and utilization tools

Despite the potential environmental benefits of the dozens of funded carbon capture, utilization, and storage (CCUS) projects [15], these technologies are not risk-free. Aside from the risk of captured CO₂ being released during long-term storage, the development of such capture and disposal technologies may significantly slow down the transition to alternative energy sources. Given this uncertainty, as well as the various risks associated with large-scale carbon capture and storage technologies, alternative approaches to carbon sequestration are required. As the most important process for converting inorganic carbon into organic matter, photosynthesis is a natural, sustainable strategy for biological

CO₂ capture and storage. Even though photosynthesis is the only process that occurs on large scale on Earth, the potential of terrestrial plants alone is not insufficient to remove a satisfactory amount of atmospheric CO₂. For example, reforestation, a widely used method for offsetting the carbon footprint, can lead to negative social consequences, such as the disappearance of pastures and source of traditional income. On the other hand, phototrophic microorganisms, particularly microalgae and cyanobacteria, have high carbon sequestration capacity during photoautotrophic growth, making them promising CO₂ removal tools [14]. It should be noted that algae perform half of the photosynthesis on Earth. They can perform photosynthesis process all year round due to their high growth rate, with additional benefits of they do not occupy large areas and are not particularly demanding in terms of growing conditions. They can grow on low-cost synthetic media, in seawater, and wastewater. Moreover, they do not compete for drinking water and arable land with food crops [16].

Microalgae can absorb carbon in the form of CO₂ via free diffusion, hydrocarbonates (HCO₃⁻) via active transport, and bicarbonates via extracellular carbonic anhydrase enzymes [17,18]. They can use CO₂ from the atmosphere as well as flue gases. According to published data, the generation of 1.0 kg of microalgal biomass can absorb up to 1.83 kg of CO₂ [19,20]. The mechanism of CO₂ assimilation in microalgae differs from the carbon cycles of terrestrial plants. Due to the inducible CO₂ concentration mechanism (CCM), microalgae and cyanobacteria can accumulate inorganic carbon in very large amounts and carry out photosynthesis even in environment of low CO₂ concentrations (2). Therefore, their contribution to biomass and oxygen (O₂) formation, as well as to CO₂ sequestration is far greater than that of terrestrial plants [21]. Many articles have been devoted to the structural organization of CCM in phototrophic microorganisms. Numerous studies have revealed the main CCM types and differences in the structure of carbon transporters and carbonic anhydrase (CA) in marine and freshwater microalgal species.

Rubisco type I is the key enzyme for CO₂ fixation in microalgae, cyanobacteria, and plants, but it has a relatively low efficiency [22,23]. Furthermore, as a competitive inhibitor of the carboxylation reaction, O₂ participates in Rubisco oxygenation side reaction and competes for enzyme availability. All of this undoubtedly affects the final productivity of photosynthetic organisms, because a significant amount of carbon is lost due to the high O₂ concentration and solubility, forming toxic phosphoglycolate molecules that are further metabolized during photorespiration at additional energy cost [24,25]. Despite the Rubisco O₂-generating activity, the enzyme carboxylation rate varies in phototrophic organisms. It is 3–5-fold higher in cyanobacteria and microalgae than in land plants. Because of the CCM concentration in the cells, the oxygenation level of Rubisco is much lower in microalgae. Various CCM types in microalgal cells have been identified. The so-called "biophysical" microalgal CCM allows for the energy-dependent active accumulation of CO₂ in the Rubisco active center while avoiding the trapping of HCO₃⁻ inorganic intermediates. The well-functioning system of CO₂ channels, membrane carriers HCO₃⁻, CA, and the acidic environment of the thylakoid lumens all contribute to this [26]. This CCM type in eukaryotic microalgae is driven by pH gradient across the thylakoid membrane and requires illumination because photosynthetic electron transport is required to generate pH differences. The formation of microcompartments containing Rubisco in microalgal pyrenoids also contributes to the accumulation of high CO₂ concentrations. According to published data, the presence of pyrenoid in algal cells leads to high CO₂ concentrations around Rubisco as CO₂ formed in the lumen of thylakoids diffuses through the tubules into the pyrenoid matrix and is fixed by Rubisco, reducing Rubisco oxygenase activity and stimulating carboxylase activity in the stroma [27–29]. Cah3, the luminal CA of the green alga *Chlamydomonas reinhardtii* [30], and O-CA in *Phaeodactylum tricornutum* diatoms have been extensively studied in this mechanism [31].

The biochemical CCM occurs in some diatoms (such as *Thalassiosira*

weissflogii) and occurs via a C_4 pathway in which HCO_3^- is converted by phosphoenolpyruvate carboxylase to oxaloacetate (compound C_4), which is then decarboxylated by malate dehydrogenase (MDH) and/or malic enzyme (ME) to CO_2 and malate, where CO_2 then enters the Calvin cycle [32,33]. According to recent data, some microalgae release a large number of CCMs simultaneously in response to low CO_2 levels. For example, Wei et al. [33], who investigated the dynamics of the transcriptome, proteome and metabolome in the microalga *Nannochloropsis oceanica* during cellular adaptation to different CO_2 concentrations, found that *N. oceanica* implements a full set of CCM in response to low carbon stress. In addition to the biophysical and biochemical CCM, there is a third type – basal CCM, provided by the activation of photorespiration and ornithine-urea cycle (OUC) genes responsible for the efficient recycling of mitochondrial CO_2 for carbon fixation by the chloroplast. The differences in the specific genes *CAS*, *PEPCK*, *ME*, and *PPDK* in response to carbon stress compared to *C. reinhardtii* and *P. tricornutum* are shown [34].

Thus, by maintaining a high CO_2 concentration in cells, CCM improves the efficiency of photosynthetic carbon fixation. CCM mechanisms in microalgae are species-specific and rely on Rubisco's selective properties [35].

Increased CO_2 concentration has a positive effect on Rubisco's kinetic properties, accelerates carboxylation and inhibits the oxygenase reaction. The critical need for photoautotrophic cultures for CO_2 may provide the foundation for an efficient method of capturing and fixing CO_2 . This is especially relevant and significant when capturing CO_2 from flue gases, where the CO_2 content is much higher than its atmospheric concentration.

There have been numerous studies on the use of streams enriched with various CO_2 concentrations for microalgae cultivation. According to the literature, the relative maximum CO_2 concentration that is optimal for the growth of most microalgal species is in the range of 5–40 %. Sydney et al. [36] reported that 5 % was the optimal CO_2 concentration for the growth of a number of microalgal strains with high biochemical potential in bioenergetics, including *Botryococcus braunii*, *C. vulgaris*, *Dunaliella tertiolecta*, and *Scenedesmus obliquus*. Schipper et al. [37] investigated four new strains isolated from the Persian Gulf, which include *Leptolyngbya* sp., *Chroococcidiopsis* sp., *Picochlorum* sp., and *Tetraselmis* sp., were tolerant to relatively high CO_2 concentrations.

The use of algae as a trap for CO_2 from flue gases has been discussed in many studies. Microalgae have a 20 % to 70 % CO_2 absorption capacity, requiring 1.3 to 2.4 kg of CO_2 per kg of dry microalgae [38]. With the production of 100 tons of microalgae biomass, approximately 180 tons of CO_2 can be consumed [39]. According to the information presented in the article by Bhola et al., microalgae have the ability to sequester CO_2 50 times more efficiently than plants. Considering that algae can produce on average about 280 tons of dry biomass per day, they are able to absorb up to 513 tons of carbon dioxide during their growth [40].

Representatives of the genera *Chlorella* and *Oscillatoria* have showed a promising ability to trap CO_2 , according to numerous researchers [41,42]. A feasibility study by Valdovinos-García et al. shows that when microalgae are cultivated in an open system with a biomass productivity of 12.71 g/m²/day, 102.13 t CO_2 /year can be captured per 1 ha of cultivated area [43]. Iglina et al. report that when cultivating algae in a pond with sunlight, a pond with a volume of 4000 m³ can absorb about 2200 tons of CO_2 per year [44].

The use of microalgae for CO_2 sequestration on an industrial scale is limited by several factors, such as the composition of flue gases and the degree of resistance of microalgae to carbon dioxide. It is known that flue gases, in addition to carbon necessary for the photosynthesis of algae, contain up to 142 different compounds, including heavy metals toxic to algae, SO_2 [40,45]. All this requires control of the flue gas composition, depending on the combustion system, generation source and combustion temperature. Also, the effective capture of CO_2 from flue gases in a power plant is limited by the varying degree of resistance

of algae to elevated levels of CO_2 . Despite the need for carbon dioxide for the metabolism of algae, for some species, high concentrations of CO_2 can be harmful and lead to a decrease in the rate of biomass growth. The main reasons for this are a large environmental load affecting the productivity of algae biomass and a decrease in pH due to the formation of bicarbonate [46].

The ability of microalgae to tolerate high concentrations of CO_2 becomes a key consideration in selecting suitable microalgae species for carbon sequestration [47]. Adding bases in the form of nitrates or genetically altering microalgae with carbonic anhydrase to limit CO_2 generation are some of the approaches to increase CO_2 tolerance in microalgae [46].

A great contribution to increasing the level of accumulation and assimilation of CO_2 by microalgae cells is also made by the development of innovative cultivation methods, in particular, the design of photobioreactor systems that ensure the efficiency of mass transfer processes. Efficient uptake of CO_2 by microalgae cells during cultivation is achieved by two approaches, such as increasing the gas-liquid interface (i.e., bubble specific surface area) and increasing bubble mass transfer time (i.e., bubble residence time) [48–50]. Therefore, the design and operation of the aerator used to create bubbles is critical to the process of CO_2 fixation by microalgae. Li et al. demonstrated the development of a new rotary mixing aerator with a magnetic drive for growing microalgae based on the principle of secondary crushing by centrifugal force and shear stress is presented [50]. Simultaneously, the duration of bubble production is shortened, the bubbles' diameter is decreased, and as a result, the bubbles' residence period is increased, enhancing the growth of microalgae and carbon fixation. Flat photobioreactor with internals of a perforated inverted-arc trough for CO_2 biofixation by microalgae is also described. These internals increase the CO_2 contact time between gas and liquid and periodically aerate the upper portion of the photobioreactor, stirring slurry, which improves the transfer of CO_2 from the gas to the culture medium [51].

Thus, the utilization of CO_2 emissions by photosynthesis of microalgae is a promising direction, providing long-term fixation of carbon dioxide in biomass, which can be converted into biofuel and other valuable products [46,52].

3. Bioenergy potential of microalgae

The carbon balance clearly shows that the energy sector is the primary source of CO_2 emission. As a result, cost-effective measures such as removing fossil fuel subsidies, reducing methane emissions from the oil and gas industry and generation of electricity from alternative sources as solar panels, wind farms, nuclear and geothermal energy sources, implemented in energy sector can reduce GHG emissions up to 100–200 million t yr⁻¹ [53]. However, policies should encourage the use of biofuels, which possess immense potential in reducing GHG emissions while utilizing the limited area of non-arable land and freshwater to maintain a balance between food, energy, and the environment. Microalgae which fulfilling all criteria above are a promising feedstock for renewable third and fourth-generation biofuels. Because phototrophic microorganisms have large metabolic capacities, they can be used to produce environmentally friendly liquid and gaseous biofuels to meet the world's growing energy demand [54,55]. In addition to carbon neutrality, other benefits of such fuels include their high biodegradability and non-toxicity, as well as the ability to co-produce other food, cosmetic, agricultural, and medical bioproducts from the remaining biomass.

Modern catalytic methods open up broad possibilities for converting microalgal biomass into a variety of CO_2 -neutral energy sources. Microalgal cultivation is less costly than terrestrial plants, and their high productivity allows for significantly greater stored chemical energy per unit area [56].

The following are the main stages of microalgae-derived biofuel production:

- Selection of microalgal strains and their cultivation;
- Biomass harvesting;
- Fuel elements (oils, alcohol, etc.) extraction from biomass via step-wise processing using various physicochemical and biological methods;
- Conversion of the fuel fractions into the desired biofuel.

At the same time, thermochemical, biochemical, or chemical technologies can be used to produce various biofuels from microalgal biomass, including both liquid biofuel (biodiesel, biobutanol, bioethanol, and bio-oil) and gaseous biofuel (methane (CH₄) and biohydrogen (bio-H₂)) [38,57,58].

3.1. Biobutanol and bioethanol

In recent years, researchers' attention has shifted to the use of microalgal biomass for the production of alcohol-based biofuels – ethanol and butanol – as the most realistic types of biofuels, which offer tremendous potential in bioenergy as alternatives to gasoline [59,60]. Ethanol is currently the most widely used renewable biofuel, produced by *Clostridium*, *Zymomonas mobilis*, and the yeast *Saccharomyces cerevisiae* fermentation utilizing food starch or lignocellulose as substrate [61]. Although ethanol currently has the highest tonnage among all biofuel, experts discovered significant advantages of butanol after comparing the properties of biobutanol and bioethanol as fuel components [62]. Compared to ethanol, butanol is more economical, contains 25 % more energy, is safer to use and transport, which is ensured by its lower volatility and less aggressive properties, and does not form sulfur or nitrogen oxides during combustion, it is considered a more environmentally friendly fuel.

Fermentation of carbohydrate feedstocks of plant origin (maize and beet) and various wood wastes, impacting the cost of the final product due to various technical problems related to the pre-processing of plant-based feedstocks [63], which is the most common method of producing biobutanol by microbiological synthesis. Algae have great potential as a feedstock for the production of alcoholic biofuels because they accumulate a high level of carbohydrates. Tables 1 and 2 summarize the performance of utilizing algal biomass for bioethanol and biobutanol production. It is important to take note that not only microalgal biomass but also the waste produced after lipid isolation in biodiesel production can be used to produce alcoholic fuels.

One of the major challenges in producing any type of microalgae-based (including cyanobacteria-based) biofuel is unsatisfactory final product yield, which is being addressed by various research strategies. When using microalgal feedstocks, the insufficient yield of the final product – butanol or ethanol – is being addressed using a variety of approaches, including optimization of fermentation medium. For example, the addition of carbon substrate (acetic and butyric acids), which are the main precursors in the second phase of ABE fermentation, increased butanol yield significantly [64]. Butyric acid mediated a significant increase in butanol synthesis from red algae up to 4.48 g l⁻¹ (about 30-fold), with a maximum yield of reducing sugars of 0.35 g DW⁻¹ in the presence of butyrate [65].

There is no doubt that genetic engineering has advanced significantly in this area. Genetic engineering technologies not only enhance the accumulation of carbohydrates in phototrophic microorganism cells [75], but also creating microalgal strains that produce alcohol. *Synechocystis* sp. PCC 6803, for example, was found to overexpress heterologous genes encoding pyruvate decarboxylase (PDC) from *Zymomonas mobilis* and NADPH-dependent alcohol dehydrogenase (*YqhD*) from *Escherichia coli* [76]. To improve biofuel production, specific genes and pathways for alcohol resistance have been identified for this strain. The strain *Synechocystis* sp. PCC 6803 produced ethanol at a rate of 248 mg l⁻¹ d⁻¹, making it a valuable biosystem for photosynthetic ethanol production (Table 2) [77].

In general, many microalgae have own enzymatic pathway to

Table 1

The yield of bioethanol produced by various microalgal strains.

Microalgae strain	Fermentation condition	Bioethanol yield, g L ⁻¹	Reference
<i>C. reinhardtii</i> CC 2656	pH 6.5–7.0, S. fermentation with <i>S. cerevisiae</i> INVSC-1 at 30 °C for 36 h, initial acetate and ammonium chloride concentration of 1.56 g L ⁻¹ and 100–200 mg L ⁻¹	4.25	[66]
<i>Chlorella</i> sp.	Pre-treated with 1.5 % sulfuric acid, fermentation with <i>S. cerevisiae</i> TISTR 5339, hydrolyzing the pre-treated slurry with α-amylase and glucoamylase	5.6	[67]
<i>Chlorella vulgaris</i> ESP-31	Pre-treated with 1.5 % sulfuric acid, fermentation with <i>Saccharomyces cerevisiae</i> FAY-1 at 30 °C for 48 h	4.2	[68]
<i>Chlorella vulgaris</i>	acid pre-treatment 10 % 2 N H ₂ SO ₄ , at 121 °C for 45 mins pH 4.8, fermentation with co-culture of <i>S. cerevisiae</i> and <i>A. niger</i> at 30 °C for 120 h	0.33	[69]
<i>Chlorella</i> sp.	Enzymatic hydrolysis - cellulase (<i>Trichoderma longibrachiatu</i>), fermentation with <i>S. cerevisiae</i> at 27 °C, for 96 h	1.0	[70]
<i>Chlorella sorokiniana</i>	Simultaneous saccharification and fermentation (SSF), using <i>S. cerevisiae</i> at 20 % v/v at 33.94 °C, pH 5.55, biomass: 16.95 g L ⁻¹	8.1 ^a	[71]
<i>Chlamydomonas</i> sp. KNM0029C	Sonication and amylase Fermentation with <i>S. cerevisiae</i>	12.87	[72]
<i>Dunaliella tertiolecta</i>	hydrolyzed with H ₂ SO ₄ 1 % (v/v) at 120 °C for 15 min, fermentation with <i>S. cerevisiae</i> at 30 °C for 24 h	0.41 ^b	[73]
<i>S. cerevisiae</i> ATCC	Pre-treatment and hydrolysis: 0.5 mol/L H ₂ SO ₄ and 2.5 % MgSO ₄ at 121 °C for 40 min. Fermentation: <i>S. cerevisiae</i> ATCC 7921 at 30 °C for 24 h	9.96	[74]

^a Calculated from g ethanol g⁻¹ glucose.

^b Calculated from g ethanol g⁻¹ DW.

produce ethanol, but changes in regulatory pathways or the creation of new metabolic pathways are required to produce ethanol via photoautotrophic metabolism. Because their cells contain intermediates and alcohol precursors, such possibilities are real. Thus, some of the 2-keto-butyrate used by the cell for amino acid synthesis can be diverted into isobutanol production [84].

The green unicellular microalga *C. reinhardtii* is an appropriate model for genetic manipulations to increase the accumulation of carbohydrates for fermentative ethanol production. Starch accumulation was increased in transformed mutant strains of *C. reinhardtii* sta7–10 (c5) and sta7–10 (c19) [83]. The amylase gene of the hyperthermophilic bacterium *Thermotoga neapolitana* was transformed into *C. reinhardtii* genome to improve the extraction of fermentable carbohydrates, reducing additional pre-treatment processes and thereby facilitating biomass use for bioethanol or biobutanol production [85].

Thus, the key advantages of algae are their incredibly fast growth rate and high carbon dioxide binding, converting them into carbohydrates, which can be easily converted into alcohol fuel. Also, the great opportunities opened up by modern genetic engineering can help speed up the solution of energy problems through the production of cheap biosynthetic butanol and ethanol.

Table 2

The yield of biobutanol produced by various microalgal strains.

Microalgae strain	Fermentation conditions	Butanol yield, g L ⁻¹	Reference
<i>C. vulgaris</i> FSP-E	Ethanol was examined with an ethanol-producing bacterium <i>Z. mobilis</i> ATCC 29191 at 45 °C. Before fermentation the biomass was treated with enzymes (endoglucanase: 0.61 U mL ⁻¹ , b-glucosidase: 0.30 U mL ⁻¹ , Amylase: 0.75 U mL ⁻¹)	11.7	[78]
<i>C. vulgaris</i> sp. ESP6	The butanol fermentation of <i>C. acetobutylicum</i> ATCC824 was conducted at a controlled temperature of 37 °C. Glucose alone, xylose alone, and the mixture of the two with a glucose were used as the carbon source	0.93	[79]
<i>Borodiniellopsis texensis</i> CCALA 892	Cultivated in municipal wastewater, fermentation with <i>C. acetobutylicum</i> , reacted with 0.5 N H ₂ SO ₄	3.63	[80]
<i>Chlorella</i> sp. DEE006	Acidic hydrolysis (1 M H ₂ SO ₄ fermentation carried out with <i>C. acetobutylicum</i> at 37 °C	6.23	[81]
<i>Chlorella vulgaris</i> JSC-6	The butanol fermentation was conducted <i>C. acetobutylicum</i> ATCC824 at a 37 °C without pH control	13.1	[82]
<i>Chlorella zofingiensis</i> CCALA 944	Cultivated in municipal wastewater and Indole-3-acetic acid (IAA) via hydrogen peroxide (H ₂ O ₂) pre-treatment	4.2	[83]
<i>B. texensis</i> CCALA	<i>Borodiniellopsis texensis</i> CCALA 892 biomass directly cultivated in a 25 % of wastewater	3.63	[80]

3.2. Biodiesel

Biodiesel, which can be used in blends or directly in various diesel engines, can also significantly contribute to increasing the share of renewable energy in the energy balance. Although various vegetable oils and animal fats are currently used in industrial biodiesel production, the higher oil yield of non-food algal biomass compared to food oilseeds enables the cost-effective conversion of microalgal biomass into biodiesel using various technologies.

Microalgae accumulate in cells non-polar storage lipids triacylglycerides, which can be easily converted into fatty acid methyl esters during transesterification, which is an important and universal form of biodiesel fuel. At the same time, it is known that the optimal conditions for the production of microalgae biomass are not necessarily optimal for the accumulation of lipids. Moreover, triacylglycerides accumulate better under nutrient stress, providing a storage function for the cell under adverse conditions. Therefore, to stimulate lipid biosynthesis, it is necessary to reprogram physiological pathways, which is the aim of various strategies and approaches to increase lipid productivity and ensure the stability and scalability of this process. Currently, representatives of the genera *Scenedesmus*, *Chlorella*, *Ankistrodesmus*, *Chlamydomonas*, *Tetraselmis*, *Nannochloropsis*, *Botryococcus*, *Neochloris*, etc. are well studied in terms of lipid accumulation [86,87]. Depending on the species, they can accumulate considerable quantities of triacylglyceride (TAG) as a storage lipid under photooxidative stress or other harsh environmental conditions (Table 3).

Metabolic engineering, which aims to disrupt competing metabolic pathways, is an efficient method for boosting lipid accumulation in microalgal cells. It is possible to enhance the directional metabolic flux towards lipid biosynthesis by blocking the carbohydrate synthesis pathway, namely enzymes operation, because carbohydrate and lipid synthesis share common carbon precursors in microalgae. Consequently,

Table 3

Biodiesel yield produced by various microalgal strains.

Microalgae strain	Technique	Total lipid content, % DW ⁻¹	References
<i>Chlorella vulgaris</i>	Catalyst is utilized with varying Na loadings	56.4	[88]
<i>N. oculata</i>	Catalyst is utilized with varying Na loadings	47.1	
<i>C. vulgaris</i>	Electrolysis using CaO/KOH-Fe ₃ O ₄ and KF/KOH-Fe ₃ O ₄ as magnetic nanocatalysts	39	[89]
<i>C. vulgaris</i>	Homogenous Acid-catalyzed in situ Transesterification with Microwave Irradiation	22.9	[90]
<i>Botryococcus braunii</i> sp. LB-572	Homogenized cells monitored in gas chromatography then the lipids were extracted by Folch method	26.8	[91]
<i>Botryococcus braunii</i> UTEX 572	The lipid fraction was extracted with chloroform/methanol (2:1, v/v) under a vacuum.	63	[92]
<i>Dunaliella salina</i>	Different treatments (salinity, acidity, nutrients) under light	31.5	[93]
<i>Botryococcus braunii</i> LEM 14	Lipids were determined by extraction with methanol: chloroform 1:1, followed by a liquid-liquid extraction with hexane	36.1	[94]
<i>Botryococcus braunii</i> Kütz No LB 807/1	The lipid sample was determined by chloroform-methanol (2:1).	17.8	[95]
<i>Tetraspora</i> sp.	Homogenization and different concentrations of NaOH as the catalyst	60	[96]

inhibiting ADP-glucose pyrophosphorylase, which catalyses starch synthesis, increased TAG accumulation in *Chlamydomonas* from 2 to 20.5 % of dry weight. Inhibiting UDP-glucose pyrophosphorylase (UGPase) activity can result in lipid overproduction. Consequently, using an effector, the TAG content was raised 45-fold by disrupting the UGPase gene in the *Phaeodactylum tricornutum* strain [97]. Knockdown of the phosphoenolpyruvate carboxylase (PEPC) isoform mRNA by RNA interference increased the TAG content in wild *Chlamydomonas reinhardtii* from 2.77 to 3.33 % of dry weight [98]. Knockdown of multifunctional lipase/phospholipase/acyltransferase in the diatom *Thalassiosira* resulted in a fourfold increase in TAG. Overexpression of the plastid lysophosphatidic acid acyltransferase in *Neochloris oleoabundans* also contributed to a 2.4- and 2.8-fold increase in lipid and TAG productivity, respectively [99]. Thus, blocking competing metabolic pathways, especially PEPC, is a promising target for genetic transformation. In general, multiple studies have thoroughly examined the currently available arsenal of metabolic engineering techniques for increasing lipid productivity [100 – 102]. It should be highlighted that they are particularly relevant for fast-growing, productive cyanobacterial strains that have a low lipid content and hence aim to increase their lipid productivity. Many of these genetic engineering options encourage the investigation of microalgae as a possible source of biodiesel feedstock [102,103].

Furthermore, not only high lipid productivity, but also the correct fatty acid profile, are important parameters in the selection of microalgae species for biodiesel production. An important parameter determining the quality of biodiesel fuel is the composition of fatty acid esters, the structure of which influences the key properties of the biofuel, in particular the cetane number, ignition temperature, viscosity, oxidative stability and flowability at low temperatures [87]. Biofuels containing compounds with a large number of saturated bonds are characterized by higher oxidative stability; polymerization of glycerol

does not occur during combustion, which significantly increases engine reliability [104]. Among the fatty acids, the chemical compositions C10:0, C16:1, and C18:1 are important for biodiesel production.

Mutagenesis and genetic engineering can also be used to change the quantitative and qualitative composition of lipids in biodiesel producers. For example, the mutant strain of *Isochrysis* sp. obtained through induced mutagenesis accumulated up to 52.3 % saturated fatty acids and 29.3 % monounsaturated fatty acids, with a significant 1.3-fold increase in C16-C18 content compared to the original wild-type strain, allowing us to consider it a promising candidate for biodiesel production [105]. Starch-free mutant strains of the microalga *Scenedesmus obliquus* accumulate up to 45 wt% of the biofuel precursor triacylglycerol, according to Jaeger et al. [106].

Thus, in determining the potential of microalgae for biodiesel production, it should be noted that they are extremely prolific, develop biomass rapidly, and may accumulate 50–300 times more lipid product than other sources [107]. However, even though biodiesel production from microalgae is not yet commercially established due to high capital costs, substantial progress in technological and economic development has been accomplished in this system in recent years.

Several feasibility studies have found considerable variances in production costs due to both varied growing conditions and different processing methods, resulting in varying biofuel costs. Additionally, the region where the production is located, which impacts the number of working days, salaries, and energy costs, are major criteria influencing the cost of biodiesel production from microalgal biomass [108]. The cost of biodiesel from microalgal biomass was estimated to be \$13.31 per gallon on average, depending on the cultivation procedure, biomass yield, lipid content, extraction technologies, and production scale [109]. Kang S. (2019) related lipid accumulation efficiency to strain species characteristics; in this context, the cost of biodiesel production he calculated varied by species and was 6.5, 7.0, and 8.3 USD/kg for *Chlorella vulgaris*, *Tetraselmis suecica*, and *Nannochloropsis*, respectively [110]. According to Batan et al. (2016), the cost of 3.46 USD/L algal biodiesel for an annual photobioreactor production of 37.85 million litres of biofuel is reliant on market access to related products. This presupposes that the crops are used to produce a higher value co-product in addition to fuel and energy [111]. The main strategies for reducing the cost of algal biodiesel described in the literature are listed in Table 4.

Among the primary cost-cutting strategies for algal biodiesel, I would like to highlight the integration of biofuel production with the associated production of other valuable products, biologically active substances, and other types of biofuels, which provides an opportunity to increase economic competitiveness. Furthermore, when microalgal biomass production is integrated with wastewater treatment in bioremediation processes, further economic benefits can be realised.

Table 4
Main strategies to reduce the cost of algal biodiesel.

Initial cost of biodiesel, \$/L	Strategy applied	Final cost of biodiesel, \$/L	Reference
9.9	Obtaining highly productive strains (lipid accumulation)	4.5	[112]
3.02–3.06	Development of highly efficient dehydration and extraction technologies	2.92	[113]
2.26	Use of cheap raw materials (flue gases, wastewater):	0.50	[114]
12.6		4.8	
	• Open systems		
	• Photobioreactor		
17.26	Integration with obtaining	13.73	[108,115,116]
3.90	other valuable products:	0.54	
72		47	
	• Protein		
	• Astaxanthin		
	• Biogas		

Numerous studies, for example, have established the feasibility of producing oleaginous microalgae in wastewater, with microalgae demonstrating substantial effectiveness in removing contaminants from wastewater and enriching lipids [117]. The utilization of wastewater and flue gases in the production of biodiesel microalgae is a key part of the development process since it may greatly cut production costs, thereby lowering the cost of biodiesel.

3.3. Biohydrogen

Biohydrogen, as a gaseous fuel, may currently offer the least painless transition to more promising forms of energy from an environmental point of view. With the concept of the ‘green economy’, hydrogen (H₂) is a promising, eco-friendly, and carbon-free energy source with high-energy density (142 kJ g^{−1}) and practically the only fuel with water as the combustion product. However, the current commercial-scale H₂ production strategies such as natural gas/oil steam reforming, coal gasification, biomass gasification/pyrolysis, water electrolysis and thermolysis are environmentally harmful and energy-intensive [118,119].

H₂ can be produced in two ways by microalgae, which are water biophotolysis and dark fermentation using hydrogen-producing bacteria. Microalgae-based H₂ production via water biophotolysis is attracting the attention of researchers since microalgae potentially do not require organic carbon and can produce H₂ from water and sunlight. The production of hydrogen is associated with the implementation of oxygenic photosynthesis by microalgae, where oxygen and hydrogen are formed simultaneously, but in different photosystems [120,121]. However, the high sensitivity of hydrogenase to oxygen inhibits the process of hydrogen production. Therefore, stressful conditions are created, such as sulfur and oxygen starvation to increase the duration of the process of hydrogen evolution. The creation of such conditions contributes to a decrease in the level of activity of photosystem II, which leads to reversible inactivation of oxygen evolution and, thus, an increase in hydrogenase activity and H₂ production. The main studies were carried out with a strain of green microalgae *Chlamydomonas reinhardtii* in this direction [122]. The strains *Scenedesmus obliquus*, *Tetraspora* sp., *Chlorococcum littorale*, *Platymonas subcordiformis*, *Chlorella vulgaris*, and *Chlorella fusca* also have hydrogenase activity [69]. Bio-H₂ production by various microalgae strains is shown in Table 5.

Despite the ability of microalgae to produce hydrogen, the rate of formation is low and does not exceed 3 ml l^{−1} h^{−1}. The existing flaws of photosynthetic bio-H₂ production by microalgal cells, such as O₂ sensitivity, make it difficult to commercialize the process. Therefore, at present, research in this area is aimed at developing various methods for improving hydrogen production by direct biophotolysis [132,133].

So, in addition to employing sulfur starvation to increase hydrogenase activity, researchers have focused on the use of various chemical adsorbents. The use of oxygen adsorbent significantly increased hydrogenase activity, while the microalgae culture remained photosynthetically active during the H₂ production phase [134]. Treatment with NaHSO₃ effectively inhibited photosystem II activity, resulting in decreased O₂ content and increased hydrogenase activity and, accordingly, a 200-fold increase in H₂ production in *Chlamydomonas reinhardtii* [135]. Many research works are devoted to promoting hydrogenase activity by creating mutant strains of microalgae. Basically, these mutations aim to modulate photosynthetic electron flow by redistributing light-harvesting complexes between PSII and PSI, resulting in high starch accumulation, which is critical for subsequent PSII-independent hydrogen production [136]. Thus, mutants of the microalgae *C. reinhardtii* with reduced levels, activity, and stability of RuBisCO were obtained, which demonstrated higher hydrogen production compared to the wild type [137].

Overexpression of type II NADH dehydrogenase was achieved in the *C. reinhardtii* CrNDA2 transplastomic mutant using plastid genome transformation [138,139]. Under conditions of sulfur starvation, this

Table 5The bio-H₂ yield produced by various microalgal strains.

Microalgae strain	Pre-treatment	Operating condition	Hydrogen yield, $\mu\text{mol H}_2/\text{mg Chl/h}$	Reference
<i>C. reinhardtii</i> CC124	Short anaerobic induction, Calvin–Benson–Bassham cycle inactive by substrate limitation	22 °C, 80–90 $\mu\text{mol photons}/\text{m}^2/\text{s}$ PAR high-salt (HS) medium supplemented with HAS, TP) or TAP, chl content 50 $\mu\text{g chl (a + b)}/\text{ml}$	500	[123]
<i>Tetraspora</i> sp. CU2551	Immobilized in alginate beads	Photoperiod production in TAP-S at 29 $\mu\text{E m}^{-2}\text{s}^{-1}$ (PAR) and 36 °C	123.1	[124]
<i>Chlamydomonas reinhardtii</i>	Immobilized in alginate beads	anaerobic condition, sulphate free medium, at 25 °C, pH 7 and intensity of 62 $\mu\text{E}/\text{m}^2/\text{s}$	12.5	[125]
<i>C. vulgaris</i> BELJ strain G-120	Direct bio-photolysis (Light and dark culture)	light conversion efficiency (light to H ₂) of 7.7 % (average 3.2 %)	0.8	[126]
<i>Chlamydomonas reinhardtii</i>	Immobilized in alginate beads	14 h sulfur depleted photoperiod at 75 $\mu\text{mol photons m}^{-2}\text{s}^{-1}$ (PAR) and 25 °C	25	[127]
<i>C. reinhardtii</i>	Co-culturing with bacteria <i>Pseudomonas putida</i> , <i>Escherichia coli</i> , <i>Rhizobium etli</i>	24 °C, PPFD of 60–90 $\mu\text{mol photons m}^{-2}\text{s}^{-1}$, acetic acid concentration 17.4 mM, pH 7.2	40.8	[128]
<i>C. reinhardtii</i> L159I–N230Y	Immobilized in alginate beads	Sulfur-depleted culture medium TAP-S used at 28 °C, pH = 7.2	12.5	[129]
<i>C. reinhardtii</i> CC124	Genetic and metabolic engineering of <i>C. reinhardtii</i>	Photomixotrophically grown cultures used in the batch process regime at 140 $\mu\text{E}/\text{m}^2/\text{s}$ in sulfur depleted TAP-S medium	31.2	[130]
<i>Chlorella</i> sp. KLS61	Normal cells	Continuous shaking in normal TAP medium at 120 rpm, 45.9 $\mu\text{mol photons m}^{-2}\text{s}^{-1}$ light	753	[131]
<i>Tetraspora</i> sp. CU2551	Immobilized alginate matrix	129 $\mu\text{mol photons m}^{-2}\text{s}^{-1}$, 24 h, 36 °C, pH 7.2, TAP-S in air	17.5	[124]

mutant demonstrated higher production of hydrogen via the indirect pathway compared to the wild type. Other researchers using the same model organism *Chlamydomonas reinhardtii* have constructed and tested the ferredoxin hydrogenase fusion protein in vivo [140]. They showed that the Fd-HydA fusion enzyme, which is characterized by a higher resistance to oxygen than native HydA, is able to intercept photosynthesis electrons and use them to produce hydrogen, while the rate of photosynthetic hydrogen production increased by 4.5 fold. The second way to produce hydrogen based on microalgae is dark fermentation using hydrogen-producing bacteria, where microalgae act as feedstock [141,142]. Although there has been research in this direction in recent years, the potential of biohydrogen production is usually low, and a pretreatment step is required to convert polymeric carbohydrates into monomeric sugars to increase their availability to microbes. Data are presented on physical, chemical and biological methods of pretreatment of microalgae biomass to facilitate the depolymerization of carbohydrates and thus increase the production of biohydrogen [143,144]. Despite the existing prospects for photobiological H₂ production by microalgal cells, there are still difficulties that stand in the way of large-scale production. The level of microalgae-based H₂ production is currently insufficient for commercial production as a competitive energy carrier, at the current state of science and technology development, production will cost more than conventional fuels in most countries of the world [145].

The main issue is the low ability of microalgae to produce H₂. This factor has the potential to be a significant impediment to the development of photobiological H₂ production as a fuel, necessitating a thorough examination of the processes involved in increasing microalgal H₂ productivity [146].

4. Carbon dioxide bioconversion into valuable products

It is well known that climate change and its consequences cannot be solved without acknowledging the key role of industrial and food production systems in the climate crisis and its preservation. The products enter global processing and transportation chains, generating large amounts of byproducts and wastes with high carbon emissions. Fossil fuels are used at almost every stage of the food supply chain, from chemicals (pesticides and synthetic fertilizers) to fuel-consuming agricultural equipment and processing, packaging, and transportation, which account for 44–57 % of total GHG emissions. Consequently, the global food supply system is a major contributor to global warming and

environmental degradation [147].

The “carbon neutrality” concept encompasses not only direct strategies to remove GHGs from the atmosphere but also a variety of compensation projects aimed at improving the ecological state of environmental matrices. Simultaneously, these projects should not only be understood as afforestation projects, but also as projects aiming at sustainable development, such as the development of technologies to increase crop yields and livestock productivity, and the development of low-waste or waste-free technologies in the polymer industry. Microalgae have significant potential for agricultural biotechnology, medicine, and the polymer industry due to their large metabolic capacities and high productivity.

4.1. Microalgae-based bioplastic

Global demand for plastic-based materials is increasing dramatically, emphasizing the workload on existing infrastructure. The increasing use of petroleum-based materials endangers the environment, particularly the marine ecosystem. Significant amounts of GHGs are released during the extraction and transportation of fossil fuels used to manufacture plastics [148]. Direct emissions can be identified as follows: methane (CH₄) leakage and combustion; fuel combustion and energy consumption during field development; and disturbance of the natural landscape (forests and fields) beneath wells and pipelines. In countries where crude oil is the primary raw material for plastics production, its extraction and transportation emit approximately 108 million tons of CO₂ annually [149]. In 2015, global emissions from ethylene cracking ranged between 184.3 and 213.0 million tons of CO₂, which is roughly equivalent to the emissions from 45 million passenger cars in a single year [150]. Therefore, bioplastics derived from renewable sources are known to be more environmentally friendly, sustainable, biodegradable, and have a lower carbon footprint than petroleum-based plastics. Global bioplastics production is currently around 750,000 ton yr^{−1}, and major industrial companies that produce bioplastics are Nature Works (producing 140,000 ton yr^{−1} of polylactic acid, PLA) and Novamont (producing 35,000 ton yr^{−1} of starch-based bioplastics) [151]. Renewable (made from plants and renewable sources), petroleum-based (made from petroleum-based plastics but biodegradable), and hybrid (a combination of petroleum-based and biological sources) bioplastics are three main types of bioplastics [152].

Nowadays, bioplastics are produced from land crops such as maize and potatoes, thereby competing with the food supply. Furthermore,

producing bioplastics from plants necessitates large areas, water, and nutrients [153]. Numerous studies have shown that this type of bioplastic production is not sustainable in the long term [154,155]. Microalgae could be the best biomass source for bioplastics production as they do not compete with the food supply, can grow on waste and overproduce lipids [156]. In addition, bioplastics derived from microalgae are more sustainable, contributing to the circular bioeconomy [157]. Bioplastics derived from microalgae have applications in food packaging, pharmaceuticals, and cosmetics.

Production of microalgae-based bioplastics includes the following approaches: blending of biomass with synthetic polymers; blending of biomass with bioplastics; using biomass as feedstock for the production of polyhydroxyalkanoates (PHA); cellulose/lipid-based plastics; and the intermediates for PLA processing, i.e., production of lactic acid using microalgae as a substrate for microbes and subsequent advanced polymerization processes. Microalgal biomass can be blended with petroleum-based plastics such as HDPE (high-density polyethylene), LDPE (low-density polyethylene), PVC (polyvinyl chloride), PP (polypropylene), and PLA to effectively extend shelf life and improve the mechanical properties of microalgae-based bioplastics [158]. Due to the high protein content, two widely known microalgae, *Chlorella* (51–58 %) and *Spirulina* (46–63 %) are suitable for bioplastics production [159]. Furthermore, their relatively small cell sizes benefit not only the film and fiber markets where particle size is a limiting factor but also bioplastics production, as the pre-treatment stage can be skipped, resulting in cost-efficient large-scale production with reduced waste generation [160].

To improve the flexibility of the *S. platensis*-derived plastic, glycerol was added in different concentrations (15–30 %). The bioplastic with 30 % glycerol addition had higher tensile strength but lower elongation compared to commercial plastic bags. Therefore, this type of bioplastic can be used in industries that do not require high elongation, such as food packaging, pharmaceutical applications, or cosmetics [161].

Among various strains of microalgae (including cyanobacteria) selected from the high-rate algae pond (HRAP), *Microcystis aeruginosa* demonstrated the highest PHB concentration ($0.49 \pm 0.5 \text{ mg ml}^{-1}$). However, the biomass obtained from the HRAP was dominated by *Microcystis* sp., which had a higher concentration (0.7 mg ml^{-1}), consequently, its biomass was used for bioplastics production due to the higher PHB concentration. The elongation at break (%) of microalgae-derived bioplastics was 530 % higher than the control (307 %). It can be concluded that microalgae-based bioplastic has good plasticity [162].

Microalgae have also been considered as a new source for starch-based bioplastics production [163]. *C. sorokiniana* biomass has been used to produce starch granules (1 μm). The use of ultrasonic homogenization before mixing can improve the uniformity and surface properties of the produced *Chlorella*-polyvinyl alcohol (*Chlorella*-PVA) blends, providing an alternative for food packaging [164].

Mathiot et al. (2019) conducted research on microalgal strain selection for the manufacturing of starch-based bioplastics. They selected 10 microalgae strains, including *Chlamydomonas*, *Chlorella*, and *Scenedesmus*. The algal strains were cultivated on a low-sulfur TAP medium at 25 °C with a light intensity of $125 \text{ mol m}^{-2} \text{ s}^{-1}$ and a pH of 7.2–7.4. *Chlamydomonas reinhardtii* was found to be the most efficient strain for bioplastic production, with a starch to biomass ratio of 49 % in the medium and excellent plasticization with 30 % glycerol at 120 °C [163]. The ability of the starch-enriched microalgae to plasticize uniformly with glycerol in a twin-screw extruder was confirmed by microstructural characterization, implying that microalgae could be used as a new platform for bioplastic production.

Similarly, Kavitha et al. optimised the growth conditions for polyhydroxybutyrate (PHB) production from wastewater using *Botryococcus braunii*. The greatest PHB production ($247.0.42 \text{ mg l}^{-1}$) was produced at a concentration of 60 % wastewater as culture medium at 40 °C and pH 7.5, according to the data collected [165]. According to Das et al. the microalgae biomass remaining after lipid extraction can also be used for

the production of bioplastics, and the result shows a PHB content of 27 % [166].

Microalgae and cyanobacteria, like seaweed, are the raw materials of third-generation bioplastics. Indeed, third-generation bioplastics have received less attention since most of them are not yet commercially viable, and progress in this area has been slow. It is impossible to tell how much bioplastic based on microalgae is currently produced in this context. This area of research, however, is important and should be developed and considered as one of the weapons in the fight against climate change, as microalgae are fast growing photosynthetic organisms with the potential to convert 9–10 % of solar energy into biomass with a theoretical yield of about $77 \text{ g/biomass/m}^2/\text{day}$, which is about 280 t/ha/year. Each year, the microalgae industry produces around 7000 tons of dry biomass, reflecting the worldwide market, with revenues ranging from US\$3.8 to US\$5.4 billion [167]. These numbers demonstrate the interest of various industries, notably the packaging materials industry, in adopting biomass as a safe and sustainable solution. The intriguing and diverse composition of microalgae sugars and polysaccharides such as starch, cellulose, lignin, and chitosan underpins their potential for producing biodegradable, carbon-neutral polymers. As a result, microalgae-based bioplastics are being considered as an alternative to conventional plastics, which play an important role in environmental conservation [164].

4.2. Microalgae-based biofertilizers

The agricultural sector, using about 11 % of all available cultivated land and consuming up to 70 % of all fresh water, as well as consuming up to 30 % of the total energy supply, emits 10 Gt CO₂ per year and contributes significantly to emissions of greenhouse gases such as CH₄ and nitrous oxide (N₂O) [168].

In addition, many countries are currently experiencing significant deterioration of agricultural soils, pesticide pollution and a decline in natural fertility, leading to reduced crop quality, significant damage to human health and a massive economic and environmental crisis. Undoubtedly, the use of chemical fertilizers can provide high yields, but their rash use has a number of negative consequences, including chemical oversaturation of food crops, pollution of groundwater and the atmosphere due to the accumulation of xenobiotics in the soil, and changes in the natural soil microbiome [169].

CO₂ emissions from the large amounts of fossil fuels used in the production and transportation of chemical nitrogen fertilizers also contribute to climate change. In addition to CO₂ emissions from chemical nitrogen fertilizer plants also contain H₂, NH₃ and carbon monoxide (CO). In addition, excessive use of chemical fertilizers causes acidification and hardening of the soil, which reduces root strength and respiration and leads to a decrease in the population of beneficial microorganisms, and thus leads to loss of soil fertility [170]. Therefore, the revival of organic farming, the core of which is the use of the potential of natural living systems, in particular phototrophic microorganisms, is an effective solution to existing problems [171].

Many studies have shown that phototrophic microorganisms are increasingly used not only in bioremediation and biofuel production, but also in agriculture since microalgae can produce a wide range of bioactive compounds such as plant growth-promoting substances (e.g., phytohormones), amino acids, carotenoids, and phycobilin [172,173]. These compounds promote plant productivity by improving growth and conferring resistance to pathogens at a low environmental cost [174]. Green microalgae (*C. vulgaris*, *Scenedesmus obliquus*, *Scenedesmus acutus*, *Scenedesmus quadricauda*, and *Scenedesmus spinosa*) and N₂-fixing cyanobacteria (family *Nostocaceae*) are used for the above purposes.

Phototrophic microorganisms play an important role in maintaining soil fertility and therefore serve as natural biofertilizers [175]. The main functions of microalgae and cyanobacteria:

- improving the porosity of soil and produce adhesive substances;

- produce phytohormones (auxins, gibberellins, etc.), vitamins, and amino acids;
- improve the water-holding capacity of soil due to its gelatinous structure;
- increase soil biomass after death and decomposition;
- reduce soil salinity;
- weed control;
- improves phosphates availability in soil by releasing organic acids;
- efficient uptake of heavy metals by microbial surface (bioremediation) [176–178].

Auxin, cytokinin, abscisic acid, ethylene, and gibberellin are phytohormones found in microalgae extracts that play an important role in regulating plant growth and development. Accordingly, microalgal extracts can be used as sustainable sources for plant biostimulation [179,180]. Auxins (indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA)) being the key regulators of many developmental processes, including cell division and elongation, can either stimulate or inhibit plant growth and metabolism. Plant physiological processes such as root and shoot development, leaf senescence, nutrient mobilization, and seed germination, rely on cytokinins [181], whereas gibberellins can stimulate cell division, induce pigments and proteins accumulation, and promote cell elongation and expansion [182]. Ethylene is a gaseous phytohormone that protects plants against abiotic stresses like drought, cold temperatures, and high salinity, as well as biotic stresses like pathogen invasion. Thus, phytohormones, by interacting with each other and forming networks, not only influence plant growth and development but also activate defense systems against phytopathogens.

Recent experiments on the effects of microalgae in the field and greenhouse conditions have revealed that they stimulate germination, seedling and shoot growth, and root biomass of some crops such as lettuce, red amaranth, tomatoes, and peppers [183]. Growth stimulation (fresh (FW) and dry (DW) weights) was observed in lettuce germinated on a medium containing *C. vulgaris* extract (2 and 3 g dry microalgal extract per 1 kg soil) [184]. The observed improvements in plant growth (i.e., shoot growth, root DW and length) were linked to enhanced biosynthesis of carotenoids (*Cars*) and chlorophyll pigments (*Chls*), which may have led to improved photosynthetic activity. Similarly, *Spirulina platensis* application improved plant growth in several leafy vegetables, including arugula, red spinach, and bak choy [185]. Microalgal extracts were also found to be beneficial for fruiting vegetables such as tomatoes and peppers [186,187]. Sowing and foliar application of aqueous cell extracts or dry biomass of the green alga *Acutodesmus dimorphus* promoted germination, plant growth, and flowering of tomato plants [8]. Surprisingly, a bell-shaped concentration-response curve was observed with maximum plant growth performance achieved at an extract concentration of 3.75 g ml⁻¹. Spraying of polysaccharide extract of the blue-green alga *S. platensis* at 3-day intervals increased plant size, root DW, nodule size and quantity in tomato and pepper by up to 100 and 50 % [186,187].

The application of microalgal extracts can also help plants to cope with the two main abiotic stresses, salinity and drought [187]. The exopolysaccharides of *D. salina* mitigate the effects of different salinity levels on tomatoes by increasing the activity of antioxidant enzymes, phenolic compounds, and key metabolites of mechanisms against oxidative stress such as neophytadiene, tocopherol, stigmasterol, and 2,4-di-tert-butylphenol [187]. Salt content in wheat was also reduced by using aqueous extracts of *Chlorella ellipsoidea* and *Spirulina maxima*. This effect can be triggered by the stimulation of antioxidant components and protein content [188].

Plant biostimulation using microalgae may also influence microbial communities in the phyllosphere and rhizosphere [189]. Inoculation with blue-green algae, such as *Calothrix elenkii*, for instance, stimulated their microbiomes. Exopolysaccharide production is one of the main mechanisms for improving soil microbial community in response to blue-green algae inoculation. Exopolysaccharides, which are secreted

by many microalgal species, provide organic carbon for the growth and development of beneficial microbial strains, resulting in the formation of useful biofilms in the rhizosphere [190]. Their interaction with elements in soil aids in the dissolution, mineralization, and bioavailability of macro- and microelements, thus improving yields.

One of the advantages of utilizing microalgae-based biofertilisers is that they reduce greenhouse gas emissions by sequestering methane and CO₂ in the soil via adding more organic carbon. This is the ability to capture CO₂ in the soil as bicarbonate in a non-gaseous state to fertilise plant development. Bicarbonate is the major form of CO₂ in the soil at moderate pH (~ 7) and temperature (below 30 °C), and algae with active bicarbonate pumps can concentrate bicarbonate in the cell. The bicarbonate is then dehydrated either spontaneously or by carbonate anhydrase and the resulting CO₂ is captured by Calvin cycle activity, eventually in the form of microalgal biomass. For every g of microalgal biomass, 1.6 to 2 g of CO₂ are captured. According to Castro et al., 1 kg of microalgae-based biologics can sequester up to 3.17 kg of CO₂ while simultaneously improving plant development. Therefore, the use of biofertiliser ived from microalgae, which has a beneficial environmental impact, can be viewed as one of the approaches to reduce carbon emissions and improving the climate [191].

4.3. Microalgae-based biologically active compounds

The studies on microalgae are particularly important as a valuable source of natural active additives. Microalgae-based biologically active compounds (BACs) can be obtained directly through primary metabolism (proteins, FAs, vitamins, and pigments) or synthesized through secondary metabolism [192,193]. Many of them (cyanovirin, oleic acid, linolenic acid, palmitoleic acid, vitamins E and B12, β-carotene, phycocyanin, lutein, and zeaxanthin) have antifungal, antiviral, antimicrobial, antioxidant, and anti-inflammatory properties and can be used to treat and prevent diseases. BACs are generally accumulated intracellularly in microalgal biomass, though in some cases, these metabolites are also excreted into the environment (exometabolites).

Many BACs are natural metabolites of microalgae. These compounds have piqued the interest of scientific and industrial communities in recent years due to a wide range of applications such as human foods and animal feeds, as well as medical and pharmaceutical industries. Taking into account the enormous biodiversity and recent advances in genetic engineering, microalgae can produce a wide range of chemical compounds with diverse biological activities, including carotenoids, phycobilins, polyunsaturated FAs, proteins, polysaccharides, vitamins, and sterols [192,193].

The extraction of BACs from various microalgae such as *Arthrospira* (*Spirulina*), *Botryococcus braunii*, *Chlorella vulgaris*, *Dunaliella salina*, *Haematococcus pluvialis*, and *Nostoc* has been reported. The microalga *Chlorella* contains BACs (flavonoids, terpenoids, alkaloids, glycosides and saponins) with medicinal properties, namely antitumor, anticoagulant, antibacterial, antioxidant, and antihyperlipidaemic effects, as well as the hepatoprotective property and immunostimulatory activity of the enzymatic protein hydrolysate [194]. Many antioxidant compounds may be responsible for the functional activity of *Chlorella*. Antioxidants that have been identified as active against free radicals include lutein, α-carotene, β-carotene, ascorbic acid, and α-tocopherol. Some of them are important not only as natural colorants or additives, but they can also help slow down cancer rates and prevent macular degeneration. For example, the isolated peptide *Chlorella vulgaris* is able to inhibit AGS gastric carcinoma cells after G1 phase of cell cycle, with subsequent prevention of cell growth. This peptide showed an improvement in antioxidant properties against peroxy radicals (LOO) by 26-fold as compared to the reference compound (Trolox) [195]. The main bioactive compound of *Chlorella* is α-1,3-glucan, an immune stimulant that lowers free radicals and blood cholesterol levels. It is effective against stomach ulcers, sores, and constipation, having a preventive effect against atherosclerosis and hypercholesterolaemia, as

well as possess antitumor effect.

Chang et al. [196] investigated substances derived from *Dunaliella* and identified antibiotic properties that inhibited the growth of *Staphylococcus aureus*, *Bacillus cereus*, *Bacillus subtilis*, and *Enterobacter aerogenes*. Furthermore, *Dunaliella* demonstrated antimicrobial activity against several food-related pathogens, including *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, and *Aspergillus niger*.

Nowadays, natural dyes are steadily replacing chemically-synthesized ones, though the food industry emphasizes the latter. Moreover, public awareness of synthetic dyes endangering human health and the environment is increasing dramatically [197,198]. In this context, phototrophic microorganisms are regarded as important sources of natural pigments (*Chls*, *Cars*, and phycobiliproteins (*PBPs*)) [199]. Due to their antioxidant and immunomodulatory properties, microalgal pigments are currently used as dyes for the production of colored foods such as dairy products and confectionery. For example, *Dunaliella salina*, which grows under high salinity and light intensity conditions, produced 14 % of the dry biomass weight of carotenes, which are widely used as food additives and dyes [200]. The freshwater microalgae *Haematococcus pluvialis*, which contains more than 3 % dry weight biomass, is the best source of astaxanthin production on a large scale. Having the strongest anti-oxidative properties among carotenoids and other health benefits, natural astaxanthin is used in nutraceuticals and cosmetics, and in some countries, occasionally, to fortify foods and beverages [201,202].

Thus, the sequestration of carbon dioxide during the mass cultivation of microalgae makes it possible to obtain valuable biomass, which is a source of active biological components with the potential to be used in functional food supplements, as well as nutraceutical, cosmetic and pharmaceutical products.

5. Problems and development prospects

Despite their effectiveness, conventional carbon capture and storage methods currently under consideration are both unsafe and economically unviable due to the threat of possible CO₂ leakage poses to the environment [203]. Carbon capture by microalgae cells on industrial scale can be viewed as a novel cost-effective method for storing CO₂ and converting it into biofuels and other valuable bioproducts including biofertilizers, dietary supplements, and bioplastics. However, there are still several problems and limitations in this technology, which hinder its industrial application and the development of various innovative approaches and strategies are required [204,205]. Among them, the following main points can be noted:

1. Insufficient knowledge of thermodynamic and kinetic studies of the CO₂ absorption process. The effect of various microenvironmental conditions on the mechanism of CO₂ fixation is also not well understood [206,207]. Additional scientific studies are required to provide data to quantify and support industrial CO₂ uptake [205].
2. Inadequately high activity of microalgae as prospective biofuel producers lead to low yield of the final product. Although phototrophic microorganisms have a high metabolic capacity for the production of biofuels, their capacities are insufficient for the industrial-scale production of fuel [206,207]. The constant search for novel superior strains is pertinent and important to address this issue. Since the conditions of high biomass productivity and high accumulation of metabolites for fuel production have an inverse relationship, various approaches are employed to optimize the fermentation condition to increase the yield of metabolites. The discovery and application of genetic and metabolic engineering of microalgae is the primary focus for increasing directed biochemical productivity [208,209]. Therefore, investigations on genome sequencing and characterization of metabolic fluxes at the genome scale are essential for the accumulation of TAG in microalgae to increase lipid productivity [210,211]. In this case, it is necessary to

manipulate the key genes responsible for lipid biosynthesis. Genetic engineering not only solves the possibility of excessive accumulation of carbohydrates by cells of phototrophic microorganisms for the production of butanol and ethanol [212,213], but also helps address the problems associated with finding superior microalgae strains that can produce alcohol [212].

3. There is a need to establish an efficient and cost-effective microalgae cultivation system. Microalgae cultivation is a complicated process that involves mass and heat transfer, lighting conditions, and biological interactions [213,214]. There is currently no theoretical framework for system design and calculations for estimation of flow and mass transport in microalgae cultivation system [215]. The photokinetic, photovector, and photophobic reactions of cultures, as well as the adaptability and growth conditions of many algae species in the natural environment, have not been thoroughly examined. It is widely acknowledged that the optimal cultivation method for carbon biocapture is outdoor microalgae production. However, the possibility of bacterial, fungal, and protozoan contamination can prevent their commercial production as well as reduce system efficiency [216]. Photobioreactors, being closed systems for cultivation, excluding the possibility of contamination of the culture medium with foreign microflora, are a more suitable and efficient cultivation system for industrial purposes. In this regard, there is a need for additional research and development aimed at overcoming the difficulty of cultivation processes, with a focus on establishing a control system and creating photobioreactor systems for mass cultivation. In particular, the design of specific photobioreactors must be considered while developing appropriate instrumentation for this process. It is necessary to take a novel approach to the design improvement of photobioreactors intended for the large-scale production of biofuels because the requirements for the technical design of photobioreactors intended for the cultivation of microalgae for large-scale production of biofuels may differ from those for fermenters intended for the production of their biomass. Systems of photobioreactors should be designed with the localization of culture growth processes and metabolite production spatially separated, for instance in the case where the synthesis of gas or the accumulation of other metabolites (lipids, carbohydrates) requires the use of other nutrient media and other equally important conditions for the cultivation of these phototrophic microorganisms. It is also possible to consider the development of various large-scale photobioreactors that use CO₂ from flue gases released directly from industrial plants to produce algae on an industrial scale.
4. The high cost of substrate is another significant barrier in using microalgae to achieve carbon neutrality [217,218]. In large-scale microalgae cultivation, there is a large demand not only for water and CO₂ but also for nitrogen, phosphorus, sulfur and iron, which is considered another serious obstacle [175–177]. The optimal amount of these nutrients required for mass production must be determined through cost-benefit analysis to maximize economic gain.
5. It is necessary to optimize and improve the methods of biomass processing to extract the necessary biocomponents. The success of this technology is greatly influenced by the improvement of biomass separation techniques, the selection of solvents, and their ratios. For example, existing techniques for extraction of lipids from microalgae biomass include the use of a variety of expensive yet harmful chemical solvents, which not only have severe impacts on the environment and human health but also raise the cost of the final product [219]. To reduce the cost of biomass pretreatment, more research is required to identify and create cutting-edge solutions without solvent extraction or drying of the algal suspension.

The main problems of CO₂ utilization based on microalgae and possible solutions are shown in Fig. 2.

The creation of appropriate policies and the distribution of subsidies geared at assisting the biotechnology and bioenergy sectors are

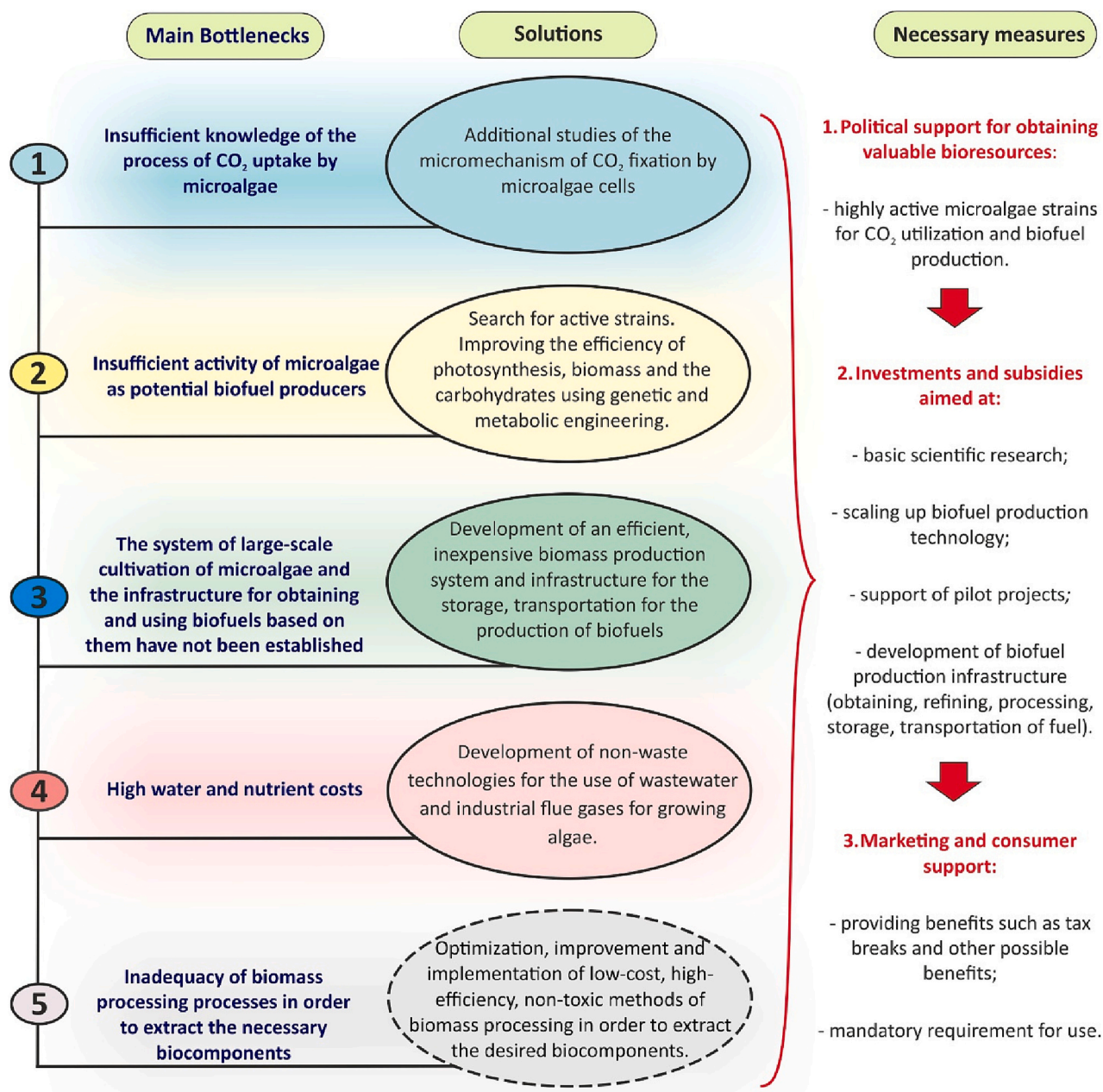


Fig. 2. The main problems of CO₂ utilization based on microalgae and possible solutions.

particularly necessary for addressing the significant constraints mentioned above. Thus, first of all, measures should be taken to stimulate the production of bioenergy, and programs for the development of biotechnologies should be developed and implemented, in which bioenergy plays a significant role. Undoubtedly, the development of this bioenergy sector will take quite a long time, however, as believed by many analysts, the development of microalgal energy can satisfy the growing needs of the world's population for fuel while assuring environmental safety [220–224].

In this regard, the primary subsidies and investments should now be dedicated primarily to the basic scientific research in carbon sequestration and bioconversion by microalgae cells into biofuels and other valuable goods [225,226]. Therefore, further research into creating superior microalgae strains using the aforementioned genetic and metabolic techniques is required for the cost-competitive production of biodiesel, hydrogen, and biobutanol. In addition, the advancement of systems biology using widely available genomic tools, high-throughput

technologies, and genetic engineering make it possible to obtain microalgae strains with the appropriate genotype [72,227]. The introduction and development of synthetic biology make it possible to individually design microalgae cells with the necessary reactions that determine them as competitive producers of biofuel cells.

In addition, subsidies and investments should be allocated to the development of infrastructure for the storage, transportation, scaling of the technology for obtaining and using biofuels, while a significant share of investments should be given to develop efficient processes for the post-treatment of the obtained biofuels, all this requires large investments in equipment and cutting-edge, modern technologies [228]. It is well known that adequate distribution infrastructure and outlets are required before biofuel production and market expansion take place, hence such governmental assistance is required.

In general, building a technological and technical foundation for the growth of this bioenergy sector, implementing modern engineering developments, producing the necessary equipment, and funding regional

projects for the production of energy and heat from biofuels all require large financial investments and political support from the state. However, the price of crude oil is currently much lower than any biofuel produced from microalgae, so it is not yet economically competitive with fossil fuels. Establishing the process of large-scale production of biofuels based on microalgae first demands capital and high operating costs. Since up to 70 % of the cost must be invested in the cultivation and harvesting of biomass, researchers are interested to the use of various wastewater for large-scale cultivation of algae biomass [229]. It is known that wastewater contains organic substances, the processing of which, according to some data, makes it possible to obtain up to 6.5 MJ kJ⁻¹ of chemical energy, which is 1 % of the total world energy [230]. This transformation of wastewater into energy involves the production of biomass, which will later be converted into energy. Thus, the use of large amount of wastewater for the cultivation of microalgae can contribute to the development of waste-free, carbon-neutral, and environmentally sustainable technologies. Also, the use of marine microalgae species suggests a reduction in freshwater sources pressure.

Thus, today microalgae, having outstanding characteristics, can be considered a promising alternative raw material for various industrial and environmental purposes. However, many efforts are required to solve various problems in mass production of biomass for high-performance biofuels and bioproducts, wastewater treatment, and CO₂ reduction. The microalgae biorefinery, a recently developed technology, intends to address the significant issues raised above and make algae-based biofuels a more sustainable and viable option. Additionally, it contributes to CO₂ emissions reduction, attractive value-added bioproduct creation, and wastewater treatment using zero-cost technology. By implementing various cost-cutting strategies, such as the utilization of industrial flue gases and wastewater as sources of nutrients and carbon, the economics of these processes can be enhanced. The microalgae-based biorefining process appears to be the most practical strategy for competition with fossil fuels and creating a sustainable and renewable source of bioenergy in the years to come.

6. Conclusions

The reduction of gas emissions and the development of renewable bioenergy have become an integral part of economic policy. The use of microalgae to reduce carbon emissions in the atmosphere can be a very viable approach to ensure a sustainable environment, especially in relation to the carbon footprint created by the transport sector. An analysis of the literature data in this area showed that microalgae have a high potential to solve this problem. Captured CO₂ from transport and industrial sites can be used to improve the algae farming system, which helps reduce CO₂ levels in the air. Microalgae, being natural absorbers of CO₂, ensure the bioconversion of captured carbon dioxide into biofuels and other valuable products. This cyclical process is consistent with the concept of carbon neutrality. Microalgae, which have higher productivity, shorter doubling time, and a higher photosynthesis rate than plants, can grow efficiently under both heterotrophic and mixotrophic conditions in the presence of organic carbon compounds and thus follow three different growth patterns able to withstand different environments, from freshwater to water with high alkalinity. The production of mutant microalgae using genetic approaches, followed by the right metabolic approach to increase the yield of the final product, and the development of innovative methods for their cultivation will contribute to the development of the sectors of bioenergy, polymer industry and agrobiotechnology.

CRedit authorship contribution statement

AKS, BDK, SIA, JSC main idea construction; AKS, JSC, HB, MOB analysis and writing original draft preparation; BDK, BKZ, ZH figure drawing; AKS, BDK, HB, ZH, MOB literature survey; BKZ, AKS, SIA, project administration, advising: AKS, BDK, YKL, HFA, TT, SIA, JSC final

preparation of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This research was funded by the Ministry of Education and Science of the Republic of Kazakhstan under these projects: AP09260077, AP13067574, AP09260785, AP14869048. HFA gratefully acknowledges support from the Distinguished Scientists Fellowship Programme, King Abdulaziz University, Saudi Arabia. SIA and JSC were supported by the joint grant RSF-MOST (22-44-08001). JSC gratefully acknowledges the financial support from the Taiwan Ministry of Science and Technology (grants MOST-110-2221-E-029-004-MY3, 111-3116-F-006-004, 111-2621-M-029-002). ZH gratefully acknowledges support from the Tianjin Synthetic Biotechnology Innovation Capacity Improvement Project (TSBICIP-IJCP-001, TSBICIP-BRFI-007, TSBICIP-BRFI-008). The present work was also financially supported in part by Grants-in-Aid for Scientific Research, Japan (No. 21K06101 (T.T.)). Fig. 1 was supported under the state contract of the Ministry of Science and Higher Education of the Russian Federation (Project No. 122050400128-1).

References

- [1] C. Le Quéré, R.B. Jackson, M.W. Jones, A.J.P. Smith, S. Abernethy, R.M. Andrew, A.J. De-Gol, D.R. Willis, Y. Shan, J.G. Canadell, P. Friedlingstein, F. Creutzig, G. P. Peters, Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement, *Nat. Clim. Chang.* 10 (2020) 647–653, <https://doi.org/10.1038/s41558-020-0797-x>.
- [2] G.P. Peters, R.M. Andrew, J.G. Canadell, P. Friedlingstein, R.B. Jackson, J. I. Korsbakken, C. Le Quéré, A. Peregon, Carbon dioxide emissions continue to grow amidst slowly emerging climate policies, *Nat. Clim. Chang.* 10 (2020) 3–6, <https://doi.org/10.1038/s41558-019-0659-6>.
- [3] C. Le Quéré, J.I. Korsbakken, C. Wilson, J. Tosun, R. Andrew, R.J. Andres, J. G. Canadell, A. Jordan, G.P. Peters, D.P. van Vuuren, Drivers of declining CO₂ emissions in 18 developed economies, *Nat. Clim. Chang.* 9 (2019) 213–217, <https://doi.org/10.1038/s41558-019-0419-7>.
- [4] S. Solaymani, CO₂ emissions patterns in 7 top carbon emitter economies: the case of transport sector, *Energy* 168 (2019) 989–1001, <https://doi.org/10.1016/j.energy.2018.11.145>.
- [5] C. Sohrabi, Z. Alsafi, N. O'Neill, M. Khan, A. Kerwan, A. Al-Jabir, C. Iosifidis, R. Agha, World Health Organization declares global emergency: a review of the 2019 novel coronavirus (COVID-19), *Int. J. Surg.* 76 (2020) 71–76, <https://doi.org/10.1016/j.ijsu.2020.02.034>.
- [6] R.J. Andres, T.A. Boden, F.M. Bréon, P. Ciais, S. Davis, D. Erickson, J.S. Gregg, A. Jacobson, G. Marland, J. Miller, T. Oda, J.G.J. Olivier, M.R. Raupach, P. Rayner, K. Treanton, A synthesis of carbon dioxide emissions from fossil-fuel combustion, *Biogeosciences* 9 (2012) 1845–1871, <https://doi.org/10.5194/bg-9-1845-2012>.
- [7] G.P. Peters, C. Le Quéré, R.M. Andrew, J.G. Canadell, P. Friedlingstein, T. Ilyina, R.B. Jackson, F. Joos, J.I. Korsbakken, G.A. McKinley, S. Sitch, P. Tans, Towards real-time verification of CO₂ emissions, *Nat. Clim. Chang.* 7 (2017) 848–850, <https://doi.org/10.1038/s41558-017-0013-9>.
- [8] J. Masojídek, K. Rangelová, G.E. Lakatos, A.M. Silva Benavides, G. Torzillo, Variables governing photosynthesis and growth in microalgae mass cultures, *Processes* 9 (2021) 820, <https://doi.org/10.3390/pr9050820>.
- [9] F. Creutzig, P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, R.C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, *Nat. Energy* 2 (2017) 1–9, <https://doi.org/10.1038/nenergy.2017.140>.
- [10] T. Mahanty, S. Bhattacharjee, M. Goswami, P. Bhattacharyya, B. Das, A. Ghosh, P. Tribedi, Biofertilizers: a potential approach for sustainable agriculture development, *Environ. Sci. Pollut. Res.* 24 (2016) 1–22, <https://doi.org/10.1007/s11356-016-8104-0>.
- [11] N.I.S. Abdul-Latif, M.Y. Ong, S. Nomanbhay, B. Salman, P.L. Show, Estimation of carbon dioxide (CO₂) reduction by utilization of algal biomass bioplastic in Malaysia using carbon emission pinch analysis (CEPA), *Bioengineered* 11 (2020) 154–164, <https://doi.org/10.1080/21655979.2020.1718471>.

- [12] F. Wang, J.D. Harindintwali, Z. Yuan, M. Wang, F. Wang, S. Li, Z. Yin, L. Huang, Y. Fu, L. Li, S.X. Chang, L. Zhang, et al., Technologies and perspectives for achieving carbon neutrality, *Innovation* 2 (2021), 100180, <https://doi.org/10.1016/j.xinn.2021.100180>.
- [13] P. Roslev, M.B. Larsen, D. Jørgensen, M. Hesselsoe, Use of heterotrophic CO₂ assimilation as a measure of metabolic activity in planktonic and sessile bacteria, *J. Microbiol. Methods* 59 (2004) 381–393, <https://doi.org/10.1016/j.mimet.2004.08.002>.
- [14] L. Rodríguez-López, A. Lami, M. El Ouahabi, N. Fagel, D. Álvarez, L. González-Rodríguez, S. Schmidt, R. Urrutia, Fossil pigments and environmental conditions in the oligotrophic Laja Lake in the Chilean Andes, *Anthropocene* 37 (2022), 100321, <https://doi.org/10.1016/j.ancene.2022.100321>.
- [15] M. Bui, et al., Carbon capture and storage (CCS): the way forward, *Energy Environ. Sci.* 11 (2018) 1062–1176, <https://doi.org/10.1039/C7EE02342A>.
- [16] A. Clarens, E. Resurreccion, M. White, L. Colosi, Environmental life cycle comparison of algae to other bioenergy feedstocks, *Environ. Sci. Technol.* 44 (2010) 1813–1819, <https://doi.org/10.1021/es902838n>.
- [17] T.D. Moshood, G. Nawanir, F. Mahmud, Microalgae biofuels production: a systematic review on socioeconomic prospects of microalgae biofuels and policy implications, *Environ. Chall.* 5 (2021), 100207, <https://doi.org/10.1016/j.envc.2021.100207>.
- [18] P. Kenny, K.J. Flynn, Physiology limits commercially viable photoautotrophic production of microalgal biofuels, *J. Appl. Phycol.* 29 (2017) 2713–2727, <https://doi.org/10.1007/s10811-017-1214-3>.
- [19] A.M. Miranda, A.A. Sáez, B.S. Hoyos, D.A. Gómez, G.J. Vargas, Improving microalgal biomass production with industrial CO₂ for bio-oil obtention by hydrothermal liquefaction, *Fuel* 302 (2021), 121236, <https://doi.org/10.1016/j.fuel.2021.121236>.
- [20] P.L. Show, M. Tang, D. Nagarajan, T. Ling, C.W. Ooi, J.S. Chang, A holistic approach to managing microalgae for biofuel applications, *Int. J. Mol. Sci.* 18 (2017) 215, <https://doi.org/10.3390/ijms18010215>.
- [21] Y. Jiang, W. Zhang, J. Wang, Y. Chen, S. Shen, T. Liu, Utilization of simulated flue gas for cultivation of *Scenedesmus dimorphus*, *Bioresour. Technol.* 128 (2012) 359–364, <https://doi.org/10.1016/j.biortech.2012.10.119>.
- [22] B.D. Rae, B.M. Long, M.R. Badger, G.D. Price, Functions, compositions, and evolution of the two types of carboxysomes: polyhedral microcompartments that facilitate CO₂ fixation in cyanobacteria and some proteobacteria, *Microbiol. Mol. Biol. Rev.* 77 (2013) 357–379, <https://doi.org/10.1128/MMBR.00061-12>.
- [23] A.M.C. Heurieux, J.N. Young, S.M. Whitney, M.R. Eason-Hubbard, R.B.Y. Lee, R. E. Sharwood, R.E.M. Rickaby, The role of Rubisco kinetics and pyrenoid morphology in shaping the CCM of haptophyte microalgae, *J. Exp. Bot.* 68 (2017) 3959–3969, <https://doi.org/10.1093/jxb/erx179>.
- [24] S.K. Singh, S. Sundaram, S. Sinha, Md.A. Rahman, S. Kapur, Recent advances in CO₂ uptake and fixation mechanism of cyanobacteria and microalgae, *Crit. Rev. Environ. Sci. Technol.* 46 (2016) 1297–1323, <https://doi.org/10.1080/10643389.2016.1217911>.
- [25] T.J. Erb, J. Zarzycki, A short history of Rubis CO: the rise and fall (?) of Nature's predominant CO₂ fixing enzyme, *Curr. Opin. Biotechnol.* 49 (2018) 100–107, <https://doi.org/10.1016/j.copbio.2017.07.017>.
- [26] M. Hagemann, H. Bauwe, Photorespiration and the potential to improve photosynthesis, *Curr. Opin. Chem. Biol.* 35 (2016) 109–116, <https://doi.org/10.1016/j.cbpa.2016.09.014>.
- [27] C. Fei, A.T. Wilson, N.M. Mangan, N.S. Wingreen, M.C. Jonikas, Modelling the pyrenoid-based CO₂-concentrating mechanism provides insights into its operating principles and a roadmap for its engineering into crops, *Nat. Plants* 8 (2022) 583–595, <https://doi.org/10.1038/s41477-022-01153-7>.
- [28] J. Barrett, P. Girr, L.C.M. Mackinder, Pyrenoids: CO₂-fixing phase separated liquid organelles, *Biochim. Biophys. Acta* 1868 (2021), 118949, <https://doi.org/10.1016/j.bbamer.2021.118949>.
- [29] P. Neofotis, J. Temple, O.L. Tessmer, J. Bibik, N. Norris, E. Pollner, B. Lucker, S. M. Weraduwage, A. Withrow, B. Sears, G. Mogos, M. Frame, D. Hall, J. Weissman, D.M. Kramer, The induction of pyrenoid synthesis by hyperoxia and its implications for the natural diversity of photosynthetic responses in *Chlamydomonas*, *Life* 10 (2021), e67565, <https://doi.org/10.7554/eLife.67565>.
- [30] D. Duanmu, Y. Wang, M.H. Spalding, Thylakoid lumen carbonic anhydrase (CAH3) mutation suppresses air-drier phenotype of LCIB mutant in *Chlamydomonas reinhardtii*, *Plant Phys.* 149 (2009) 929–937, <https://doi.org/10.1104/pp.108.132456>.
- [31] S. Kikutani, K. Nakajima, C. Nagasato, Y. Tsuji, A. Miyatake, Y. Matsuda, Thylakoid luminal θ -carbonic anhydrase critical for growth and photosynthesis in the marine diatom *Phaeodactylum tricornutum*, *Proc. Natl. Acad. Sci.* 113 (2016) 9828–9833, <https://doi.org/10.1073/pnas.1603121113>.
- [32] R. Tanaka, S. Kikutani, A. Mahardika, Y. Matsuda, Localization of enzymes relating to C₄ organic acid metabolisms in the marine diatom, *Thalassiosira pseudonana*, *Photosynth. Res.* 121 (2014) 251–263, <https://doi.org/10.1007/s11120-014-9968-9>.
- [33] L. Wei, M. El Hajjami, C. Shen, W. You, Y. Lu, J. Li, X. Jing, Q. Hu, W. Zhou, A. Poetsch, J. Xu, Transcriptomic and proteomic responses to very low CO₂ suggest multiple carbon concentrating mechanisms in *Nannochloropsis oceanica*, *Biotechnol. Biofuels* 12 (2019) 168, <https://doi.org/10.1186/s13068-019-1506-8>.
- [34] S. Wu, W. Gu, S. Jia, L. Wang, L. Wang, X. Liu, L. Zhou, A. Huang, G. Wang, Proteomic and biochemical responses to different concentrations of CO₂ suggest the existence of multiple carbon metabolism strategies in *Phaeodactylum tricornutum*, *Biotechnol. Biofuels* 14 (2021) 235, <https://doi.org/10.1186/s13068-021-02088-5>.
- [35] Y. Wang, D.J. Stessman, M.H. Spalding, The CO₂ concentrating mechanism and photosynthetic carbon assimilation in limiting CO₂: how *Chlamydomonas* works against the gradient, *Plant J.* 82 (2015) 429–448, <https://doi.org/10.1111/tpl.12829>.
- [36] E. Sydney, W. Sturm, J. De Carvalho, V. Thomaz-Soccol, C. Larroche, A. Pandey, C. Soccol, Potential carbon dioxide fixation by industrially important microalgae, *Bioresour. Technol.* 101 (2010) 5892–5896, <https://doi.org/10.1016/j.biortech.2010.02.088>.
- [37] K. Schipper, M. Al Muraikhi, G.S.H.S. Alghasal, I. Saadaoui, T. Bounnit, R. Rasheed, T. Dalgamouni, H.M.S.J. Al Jabri, R.H. Wijffels, M.J. Barbosa, Potential of novel desert microalgae and cyanobacteria for commercial applications and CO₂ sequestration, *J. Appl. Phycol.* 31 (2019) 2231–2243, <https://doi.org/10.1007/s10811-019-01763-3>.
- [38] S. Lage, Z. Gojkovic, C. Funk, F.G. Gentili, Algal biomass from wastewater and flue gases as a source of bioenergy, *Energies* 11 (2018) 1–30, <https://doi.org/10.3390/en11030664>.
- [39] S.M. Soni, S.S. Sankneniwar, M.A. Rasheed, P.L.S. Rao, S.Z. Hasan, Effect of various nitrogen sources on microalgal growth and lipid content in *Chlorella pyrenoidosa* NCIM 2738 and ANK-1, *Int. J. Curr. Microbiol. App. Sci.* 6 (8) (2017) 3099–3108, <https://doi.org/10.20546/ijcmas.2017.606.371>.
- [40] V. Bhola, F. Swalaha, R. Kumar, Overview of the potential of microalgae for CO₂ sequestration, *Int. J. Environ. Sci. Technol.* 11 (2014) 2103–2118, <https://doi.org/10.1007/s13762-013-0487-6>.
- [41] A.A. Al-Hussieny, H.M. Aljanabi, N.J. Imran, S.F. Hussain, Efficiency testing of algal *Chlorella Sorokina* and *Coelastrella* sp. to reduce carbon dioxide, *Int. J. Health Sci.* 6 (S6) (2022) 6900, <https://doi.org/10.53730/ijhs.v6nS6.11951>.
- [42] H. Ahmadzadeh, H.R. Pourianfar, S. Lyon, P.H. Rampelotto, The use of microalgae for coupling wastewater treatment with CO₂, *Front. Bioeng. Biotechnol.* 7 (2019), <https://doi.org/10.3389/fbioe.2019.00042>.
- [43] E.M. Valdovinos-García, D.J. Barajas-Fernández, M.A. Olán-Acosta, M.A. Petriz-Prieto, A. Guzmán-López, M.G. Bravo-Sánchez, Techno-economic study of CO₂ capture of a thermoelectric plant using microalgae (*Chlorella vulgaris*) for production of feedstock for bioenergy, *Energies* 13 (2) (2020) 413, <https://doi.org/10.3390/en13020413>.
- [44] T. Iglina, P. Iglina, D. Pashchenko, Industrial CO₂ capture by algae: a review and recent advances, *Sustainability* 14 (7) (2022) 3801, <https://doi.org/10.3390/su14073801>.
- [45] A.H. Alami, S. Alasad, M. Ali, M. Alshamsi, Investigating algae for CO₂ capture and accumulation and simultaneous production of biomass for biodiesel production, *Sci. Total Environ.* 10 (759) (2021), 143529, <https://doi.org/10.1016/j.scitotenv.2020.143529>.
- [46] H. Onyeaka, T. Miri, K.C. Obileke, A. Hart, C. Anumudu, Z.T. Al-Sharify, Minimizing carbon footprint via microalgae as a biological capture, *Carbon Capture Sci. Technol.* 1 (2021), 100007, <https://doi.org/10.1016/j.ccst.2021.100007>.
- [47] A.K. Vuppalladadiyam, J.G. Yao, N. Florin, A. George, X. Wang, L. Labeuww, Impact of flue gas compounds on microalgae and mechanisms for carbonassimilation and utilization, *Chem. Sus. Chem.* 11 (2018) 334–355, <https://doi.org/10.1002/cssc.201701611>.
- [48] Y.W. Cheng, J.S.M. Lim, C.C. Chong, M.K. Lam, Unravelling CO₂ capture performance of microalgae cultivation and other technologies for comparative carbon balance analysis, *J. Environ. Chem. Eng.* 9 (1) (2021), 106519, <https://doi.org/10.1016/j.jece.2021.106519>.
- [49] A. Xia, Z. Hu, Q. Liao, Y. Huang, X. Zhu, W. Ye, Y. Sun, Enhancement of CO₂ transfer and microalgae growth by perforated inverted arc trough internals in a flat-plate photobioreactor, *Bioresour. Technol.* 269 (2018) 292–299, <https://doi.org/10.1016/j.biortech.2018.08.110>.
- [50] N. Li, F. Zhong, S. Zhang, A. Xia, Y. Huang, Q. Liao, X. Zhu, A novel magnet-driven rotary mixing aerator for carbon dioxide fixation and microalgae cultivation: focusing on bubble behavior and cultivation performance, *J. Biotechnol.* 352 (2022) 26–35, <https://doi.org/10.1016/j.jbiotec.2022.05.007>.
- [51] M. Ndiaye, E. Gadoin, C. Gentric, CO₂ gas–liquid mass transfer and KLa estimation: numerical investigation in the context of airlift photobioreactor scale-up, *Chem. Eng. Res. Des.* 98 (2015) 53–65, <https://doi.org/10.1016/j.jclepro.2014.03.034>.
- [52] D. Moreira, J. Pires, Atmospheric CO₂ capture by algae: negative carbon dioxide emission path, *Bioresour. Technol.* 215 (2016) 371–379, <https://doi.org/10.1016/j.biortech.2016.03.060>.
- [53] T.W. Hickem, S. Siew, Carbon Capture Utilisation and Storage, Project: Carbon Capture Utilisation and Storage for Singapore (CCUS), 2019. Accessed on 19 November 2022, <https://www.researchgate.net/publication/337621313>.
- [54] S. Peng, Q. Chen, E. Liu, The role of computational fluid dynamics tools on investigation of pathogen transmission: prevention and control, *Sci. Total Environ.* 746 (2020), 142090, <https://doi.org/10.1016/j.scitotenv.2020.142090>.
- [55] S.P. Singh, J. Pathak, R.P. Sinha, Cyanobacterial factories for the production of green energy and value-added products: an integrated approach for economic viability, *Renew. Sust. Energ. Rev.* 69 (2017) 578–595, <https://doi.org/10.1016/j.rser.2016.11.110>.
- [56] S. Bagchi, S. Koley, A.K. Singh, Progress and challenges in microalgal biodiesel production, *Front. Microbiol.* 7 (2016), <https://doi.org/10.3389/fmicb.2016.01019>.
- [57] V.S. Sikarwar, M. Zhao, P.S. Fennell, N. Shah, E.J. Anthony, Progress in biofuel production from gasification, *Prog. Energy Combust. Sci.* 61 (2017) 189–248, <https://doi.org/10.1016/j.pecs.2017.04.001>.
- [58] A. Jayaseelan, G.P. Kannappan Panchamoorthy, V. Felix, M.R.M. Joselyn Monica, A conceptual review on microalgae biorefinery through thermochemical and

- biological pathways: bio-circular approach on carbon capture and wastewater treatment, *Bioresour. Technol.* 11 (2020), 100477, <https://doi.org/10.1016/j.biortech.2020.100477>.
- [59] S. Maity, N. Mallick, Trends and advances in sustainable bioethanol production by marine microalgae: a critical review, *J. Clean. Prod.* 345 (2022), 131153, <https://doi.org/10.1016/j.jclepro.2022.131153>.
- [60] S. Jagadevan, A. Banerjee, C. Banerjee, C. Guria, R. Tiwari, M. Baweja, P. Shukla, Recent developments in synthetic biology and metabolic engineering in microalgae towards biofuel production, *Biotechnol. Biofuels* 11 (2018) 185, <https://doi.org/10.1186/s13068-018-1181-1>.
- [61] T.J. Tse, D.J. Wiens, M.J.T. Reaney, Production of bioethanol – a review of factors affecting ethanol yield, *Fermentation* 7 (2021) 268, <https://doi.org/10.3390/fermentation7040268>.
- [62] G.R.M. Dowson, M.F. Haddow, J. Lee, R. Wingad, Catalytic conversion of ethanol into an advanced biofuel: unprecedented selectivity for n-butanol, *Angew. Chem. Int. Ed.* 52 (2013) 34, <https://doi.org/10.1002/anie.201303723>.
- [63] I. Salim, P. Conde, G. Feijoo, M. Moreira, The use of maize stover and sugar beet pulp as feedstocks in industrial fermentation plants – an economic and environmental perspective, *Clean Environ. Syst.* 2 (2020), 100005, <https://doi.org/10.1016/j.cesys.2020.100005>.
- [64] N.K.N. Al-Shorgani, H. Shukor, P. Abdeslahian, M.S. Kalil, W.M.W. Yusoff, A. A. Hamid, Enhanced butanol production by optimization of medium parameters using *Clostridium acetobutylicum* YM1, *Saudi J. Biol. Sci.* 25 (2018) 1308–1321, <https://doi.org/10.1016/j.sjbs.2016.02.017>.
- [65] D. Lehmann, N. Radomski, T. Lütke-Eversloh, New insights into the butyric acid metabolism of *Clostridium acetobutylicum*, *Appl. Microbiol. Biotechnol.* 96 (2012) 1325–1339, <https://doi.org/10.1007/s00253-012-4109-x>.
- [66] S. Banerjee, A. Ray, D. Das, Optimization of *Chlamydomonas reinhardtii* cultivation with simultaneous CO₂ sequestration and biofuels production in a biorefinery framework, *Sci. Total Environ.* 762 (2021), 143080, <https://doi.org/10.1016/j.scitotenv.2020.143080>.
- [67] M. Ngamsiriromsakul, A. Reungsang, Q. Liao, M.B. Kongkeittakorn, Enhanced bio-ethanol production from *Chlorella* sp. biomass by hydrothermal pretreatment and enzymatic hydrolysis, *Renew Energy* 141 (2019) 482–492, <https://doi.org/10.1016/j.renene.2019.07.156>.
- [68] P.I.G. Acebu, M.D.G. de Luna, C.Y. Chen, R.R.M. Abarca, J.H. Chen, J.S. Chang, Bioethanol production from *Chlorella vulgaris* ESP-31 grown in unsterilized swine wastewater, *Bioresour. Technol.* 352 (2022), 127086.
- [69] O.K. Agwa, I.G. Nwosu, G.O. Abu, Bioethanol production from *Chlorella vulgaris* biomass cultivated with plantain (*Musa paradisica*) peels extract, *Adv. Biosci. Biotechnol.* 8 (2017) 478, <https://doi.org/10.4236/abb.2017.812035>.
- [70] M.A. Kassim, K.M. Tan, N.A. Serri, Enzymatic hydrolysis of dilute alkaline pretreated *Chlorella* sp. biomass for biosugar production and fed-batch bioethanol fermentation, *Asia Pac. J. Sci. Technol.* 24 (2019) 554, <https://doi.org/10.14456/apst.2019.4>.
- [71] N.J. Tatel, C. Madrazo, Bioethanol production from microalgae *Chlorella sorokiniana* via simultaneous saccharification and fermentation, in: *IOP Conference Series: Materials Science and Engineering* 778, 2020, p. 012039.
- [72] E.J. Kim, S. Kim, H.G. Choi, S.J. Han, Co-production of biodiesel and bioethanol using psychrophilic microalga *Chlamydomonas* sp. KNM0029C isolated from Arctic sea ice, *Biotechnol. Biofuel* 13 (2020) 1–13, <https://doi.org/10.1186/s13068-020-1660-z>.
- [73] N. Varela-Bojórquez, R. Vélez-de la Rocha, M.Á. Angulo, Production of bioethanol from biomass of microalgae *Dunaliella tertiolecta*, *Int. J. Environ. Agric. Res.* 2 (2016) 110–116.
- [74] H. Shokrkar, S. Ebrahimi, M. Zamani, Bioethanol production from acidic and enzymatic hydrolysates of mixed microalgae culture, *Fuel* 200 (2017) 380–386, <https://doi.org/10.1016/j.fuel.2017.03.090>.
- [75] T. Osanai, A. Oikawa, M. Azuma, K. Tanaka, K. Saito, M.Y. Hirai, M. Ikeuchi, Genetic engineering of group 2 sigma factor SigE widely activates expressions of sugar catabolic genes in *Synechocystis* species PCC 6803, *J. Biol. Chem.* 286 (2011) 30962–30971, <https://doi.org/10.1074/jbc.M111.231183>.
- [76] N. Pade, S. Mikkat, M. Hagemann, Ethanol, glycogen and glucosylglycerol represent competing carbon pools in ethanol-producing cells of *Synechocystis* sp. PCC 6803 under high-salt conditions, *Microbiology* 163 (2017) 300–307, <https://doi.org/10.1099/mic.0.000433>.
- [77] Y.N. Choi, J.M. Park, Enhancing biomass and ethanol production by increasing NADPH production in *Synechocystis* sp. PCC 6803, *Bioresour. Technol.* 213 (2016) 54–57, <https://doi.org/10.1016/j.biortech.2016.02.056>.
- [78] E. Malvessi, K. Concato, S. Carra, M. Silveira, Formulation of medium for growth and production of ethanol and intracellular enzymes by *Zymomonas mobilis*, *Braz. Arch. Biol. Technol.* 49 (2006) 139–144, <https://doi.org/10.1016/j.biortech.2012.10.015>.
- [79] J. Lee, Y.S. Jang, S.J. Choi, J.A. Im, Metabolic engineering of *Clostridium acetobutylicum* ATCC 824 for isopropanol-butanol-ethanol fermentation, *Appl. Environ. Microbiol.* 78 (5) (2011) 1416–1423, <https://doi.org/10.1016/j.bej.2014.08.007>.
- [80] M. Onay, Biomass and bio-butanol production from *Borodiniopsis texensis* CCALA 892 in synthetic wastewater: determination of biochemical composition, *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi* 24 (2020) 306–316, <https://doi.org/10.19113/sdufenbed.573432>.
- [81] M. Onay, Investigation of biobutanol efficiency of *Chlorella* sp. cultivated in municipal wastewater, *J. Geosci. Environ. Prot.* 6 (2018) 40–50, <https://doi.org/10.4236/gep.2018.610003>.
- [82] Y. Wang, W. Guo, C.L. Cheng, S.H.J.S. Chang, Enhancing bio-butanol production from biomass of *Chlorella vulgaris* JSC-6 with sequential alkali pretreatment and acid hydrolysis, *Bioresour. Technol.* 200 (2016) 557–564, <https://doi.org/10.1016/j.biortech.2015.10.056>.
- [83] M. Onay, The effects of indole-3-acetic acid and hydrogen peroxide on *Chlorella zofingiensis* CCALA 944 for bio-butanol production, *Fuel* 273 (2020), 117795, <https://doi.org/10.1016/j.fuel.2020.117795>.
- [84] G.M. Figueroa-Torres, W.M.A.W. Mahmood, J.K. Pittman, C. Theodoropoulos, Microalgal biomass as a biorefinery platform for biobutanol and biodiesel production, *Biochem. Eng. J.* 153 (2020), 107396, <https://doi.org/10.21203/rs.3.rs-96301/v1>.
- [85] O. Kristiawan, U.S.F. Tambunan, Biobutanol production from microalgae *Nannochloropsis* sp. biomass by *Clostridium acetobutylicum* fermentation, *Sci. Contribution. Oil Gas* 43 (2020) 91–98, <https://doi.org/10.1016/j.biortech.2014.11.017>.
- [86] A.K. Sadvakasova, N.R. Akmuhanova, K. Bolatkhani, B.K. Zayadan, A. A. Usurbayeva, M.O. Bauenova, A.E. Akhmetkaliyeva, S.I. Allakhverdiev, Search for new strains of microalgae-producers of lipids from natural sources for biodiesel production, *Int. J. Hydrog. Energy* 44 (12) (2019) 5844–5853, <https://doi.org/10.1016/j.ijhydene.2019.01.093>.
- [87] A.K. Sadvakasova, B.D. Kossalbayev, B.K. Zayadan, S. Alwasel, S.I. Allakhverdiev, Potential of cyanobacteria in the conversion of wastewater to biofuels, *World J. Microbiol. Biotechnol.* 37 (8) (2021) 140, <https://doi.org/10.1007/s11274-021-03107-1>.
- [88] A.G. Sistiafi, D.N. Putri, Biodiesel synthesis from *nannochloropsis oculata* and *Chlorella vulgaris* through transesterification process using NaOH/zeolite heterogeneous catalyst, *IOP Conference Series: Earth and Environmental Science* 105 (2018) 012053, <https://doi.org/10.1088/1755-1315/105/1/012053>.
- [89] A. Farrokheh, K. Tahvildari, M. Nozari, Biodiesel production from the *Chlorella vulgaris* and *Spirulina platensis* microalgae by electrolysis using CaO/KOH-Fe₃O₄ and KF/KOH-Fe₃O₄ as magnetic nanocatalysts, *Biomass Convers. Biorefin.* 1 (2020) 15, <https://doi.org/10.1007/s13399-020-00688-z>.
- [90] U. Kalsum, M. Mahfud, A. Roesyadi, Biodiesel production from *Chlorella vulgaris* via homogenous acid catalyzed in situ transesterification with microwave irradiation, *IOP Conference Series: Earth and Environmental Science* 175 (2018) 012018, <https://doi.org/10.1088/1755-1315/175/1/012018>.
- [91] A. Ozkan, K. Kinney, L. Katz, H. Berberoglu, Reduction of water and energy requirement of algae cultivation using an algae biofilm photobioreactor, *Bioresour. Technol.* 114 (2012) 542–548, <https://doi.org/10.1016/j.biortech.2012.03.055>.
- [92] A. Ozkan, K. Kinney, L. Katz, H. Berberoglu, Reduction of water and energy requirement of algae cultivation using an algae biofilm photobioreactor, *Bioresour. Technol.* 114 (2012) 542–548, <https://doi.org/10.1016/j.biortech.2012.03.055>.
- [93] A.J. Moghadam, A.A. Beni, Comparison of biodiesel production from *Dunaliella salina* and *Chlorella vulgaris* microalgae using supercritical fluid technique, *S. Afr. J. Chem. Eng.* 41 (2022) 150–160, <https://doi.org/10.1016/j.sajce.2022.06.004>.
- [94] E.B. Sydney, T.E. da Silva, A. Tokarski, A.C. Novak, J.C. de Carvalho, A. L. Woiciechowski, C. Larroche, C.R. Soccol, Screening of microalgae with potential for biodiesel production and nutrient removal from treated domestic sewage, *Appl. Energy* 88 (2011) 3291–3294, <https://doi.org/10.1016/j.apenergy.2010.11.024>.
- [95] V. Ashokkumar, R. Rengasamy, Mass culture of *Botryococcus braunii* Kutz. under open raceway pond for biofuel production, *Bioresour. Technol.* 104 (2012) 394–399, <https://doi.org/10.1016/j.biortech.2011.10.093>.
- [96] A.R.B. Mustaffa, R. Ramli, N. Farahana, B. Hizamuddin, W.N.F.B.W. Mat, F.N.B. N. Tahir, M.A.B.S. Al-Azhar, M.M.B. Ishak, M. Abdullah, Production of biodiesel from green algae by transesterification process, *Malays. J. Ind. Technol.* 4 (2020), 2637–1081.
- [97] F. Daboussi, S. Leduc, A. Maréchal, G. Dubois, V. Guyot, C. Perez-Michaut, A. Amato, A. Falcatoire, A. Juillerat, M. Beurdeley, Genome engineering empowers the diatom *Phaeodactylum tricornutum* for biotechnology, *Nat. Commun.* 5 (2014) 3831, <https://doi.org/10.1038/ncomms4831>.
- [98] J. Yang, Y. Pan, C. Bowler, L. Zhang, H. Hu, Knockdown of phosphoenolpyruvate carboxykinase increases carbon flux to lipid synthesis in *Phaeodactylum tricornutum*, *Algal Res.* 15 (2016) 50–58, <https://doi.org/10.1016/j.algal.2016.02.004>.
- [99] W. Chungiatupornchai, K. Areerat, S. Fa-Aroonsawat, Increased triacylglycerol production in oleaginous microalga *Neochloris oleoabundans* by overexpression of plastidial lysophosphatidic acid acyltransferase, *Microb. Cell Factories* 18 (2019) 53, <https://doi.org/10.1186/s12934-019-1104-2>.
- [100] M.H. Liang, L. Wang, Q. Wang, J. Zhu, J.G. Jiang, High-value bioproducts from microalgae: strategies and progress, *Crit. Rev. Food Sci. Nutr.* 59 (2019) 2423–2441, <https://doi.org/10.1080/10408398.2018.1455030>.
- [101] C.F. Muñoz, C. Südfeld, M.L.S. Naduthodi, R.A. Weusthuis, M.J. Barbosa, R. H. Wijffels, S. D'Adamo, Genetic engineering of microalgae for enhanced lipid production, *Biotechnol. Adv.* 52 (2021), 107836, <https://doi.org/10.1016/j.biotechadv.2021.107836>.
- [102] N.K. Kang, K. Baek, H.G. Koh, C.A. Atkinson, D.R. Ort, Y.-S. Jin, Microalgal metabolic engineering strategies for the production of fuels and chemicals, *Bioresour. Technol.* 345 (2022), 126529, <https://doi.org/10.1016/j.biortech.2021.126529>.
- [103] S. Jeon, H.G. Koh, J.M. Cho, N.K. Kang, Y.K. Chang, Enhancement of lipid production in *Nannochloropsis salina* by overexpression of endogenous NADP-dependent malic enzyme, *Algal Res.* 54 (2021), 102218, <https://doi.org/10.1016/j.algal.2021.102218>.

- [104] U.I. Nda-Umar, I. Ramli, Y.H. Taufiq-Yap, E.N. Muhamad, An overview of recent research in the conversion of glycerol into biofuels, fuel additives and other bio-based chemicals, *Catalysts* 9 (2019) 15, <https://doi.org/10.3390/catal9010015>.
- [105] A. Gnouma, E. Sehlil, W. Medhioub, R. Ben Dhib, M. Masri, N. Mehler, W. Slimani, K. Sebai, A. Zouari, T. Brück, A. Medhioub, Strain Selection of Microalgae Isolated From Tunisian Coast: Characterization of the Lipid Profile for Potential Biodiesel Production 41 (3), 2018, <https://doi.org/10.1007/s00449-018-1973-5>.
- [106] L. de Jaeger, R.E. Verbeek, R.B. Draaisma, D.E. Martens, J. Springer, G. Eggink, R. H. Wijffels, Superior triacylglycerol (TAG) accumulation in starchless mutants of *Scenedesmus obliquus*: (I) mutant generation and characterization, *Biotechnol. Biofuel* 7 (2014) 69, <https://doi.org/10.1186/1754-6834-7-69>.
- [107] V.T. Duong, Y. Li, E. Nowak, P.M. Schenk, Microalgae isolation and selection for prospective biodiesel production, *Energies* 5 (12) (2012), <https://doi.org/10.3390/en5061835>.
- [108] N. Rafa, S.F. Ahmed, I.A. Badruddin, M. Mofijur, S. Kamangar, Strategies to produce cost-effective third-generation biofuel from microalgae, *Front. Energy Res.* 9 (2021), <https://doi.org/10.3389/fenrg.2021.749968>.
- [109] Z. Chen, L. Wang, S. Qiu, S. Ge, Determination of microalgal lipid content and fatty acid for biofuel production, *Biomed. Res. Int.* 3 (2018) 1–17, <https://doi.org/10.1155/2018/1503126>.
- [110] S. Kang, S. Heo, J.H. Lee, Techno-economic analysis of microalgae-based lipid production: considering influences of microalgal species, *Ind. Eng. Chem. Res.* 58 (2) (2019) 944–955, <https://pubs.acs.org/doi/10.1021/acs.iecr.8b03999>.
- [111] L.Y. Batan, G.D. Graff, T.H. Bradley, Techno-economic and Monte Carlo probabilistic analysis of microalgae biofuel production system, *Bioresour. Technol.* 219 (2016) 45–52, <https://pubs.acs.org/doi/10.1016/j.biortech.2016.07.085>.
- [112] J. Chen, J. Li, W. Dong, X. Zhang, R.D. Tyagi, P. Drogui, R.Y. Surampalli, The potential of microalgae in biodiesel production, *Renew. Sust. Energ. Rev.* 90 (2018) 336–346, <https://doi.org/10.1016/j.rser.2018.03.073>.
- [113] F. Delrue, P.A. Setier, C. Sahut, L. Courmac, A. Roubaud, G. Peltier, A.K. Froment, An economic, sustainability, and energetic model of biodiesel production from microalgae, *Bioresour. Technol.* 111 (2012) 191–200, <https://doi.org/10.1016/j.biortech.2012.02.020>.
- [114] Z. Kang, B.H. Kim, R. Ramanan, J.E. Choi, J.W. Yang, H.M. Oh, H.S. Kim, A cost analysis of microalgal biomass and biodiesel production in open raceways treating municipal wastewater and under optimum light wavelength, *J. Microbiol. Biotechnol.* 25 (1) (2015) 109–118, <https://doi.org/10.4014/jmb.1409.09019>.
- [115] S.S. Gupta, Y. Shastri, S. Bhartiya, Impact of protein co-production on techno-economic feasibility of microalgal biodiesel, *Comput. Aided Chem. Eng.* 38 (2016) 1803–1808, <https://doi.org/10.1016/B978-0-444-63428-3.50305-2>.
- [116] R. Harun, M. Davidson, M. Doyle, R. Gopiraj, M. Danquah, G. Forde, Technoeconomic analysis of an integrated microalgae photobioreactor, biodiesel and biogas production facility, *Biomass Bioenergy* 35 (2011) 741–747, <https://doi.org/10.1016/j.biombioe.2010.10.007>.
- [117] S. Srinuanpan, B. Cheirsilp, M.A. Kassim, Oleaginous microalgae cultivation for biogas upgrading and phytoremediation of wastewater, in: *Microalgae Cultivation for Biofuels Production*, 2020, pp. 69–82, <https://doi.org/10.1016/B978-0-12-817536-1.00005-9>.
- [118] S. Sharma, S. Agarwal, A. Jain, Significance of hydrogen as economic and environmentally friendly fuel, *Energies* 14 (2021) 7389, <https://doi.org/10.3390/en14217389>.
- [119] S. Schneider, S. Bajohr, F. Graf, T. Kolb, State of the art of hydrogen production via pyrolysis of natural gas, *Chem. Bio. Eng. Rev.* 5 (2020) 150–158, <https://doi.org/10.1002/cben.202000014>.
- [120] G.K. Kamshybayeva, B.D. Kossalbayev, A.K. Sadvakasova, S. Alwasel, S. I. Allakhverdiev, Strategies and economic feasibilities in cyanobacterial hydrogen production, *Int. J. Hydrog. Energy* 47 (69) (2022) 29661–29684, <https://doi.org/10.1016/j.ijhydene.2022.06.277>.
- [121] B.D. Kossalbayev, A.B. Kakimova, K. Bolatkhan, S. Alwasel, S.I. Allakhverdiev, Biohydrogen production by novel cyanobacterial strains isolated from rice paddies in Kazakhstan, *Int. J. Hydrog. Energy* 47 (37) (2022) 16440–16453, <https://doi.org/10.1016/j.ijhydene.2022.03.126>.
- [122] V. Nagy, A. Vidal-Meireles, A. Podmaniczki, K. Szentmihályi, G. Rákhely, L. Zsigmond, L. Kovács, S.Z. Tóth, The mechanism of photosystem-II inactivation during Sulphur deprivation-induced H₂ production in *Chlamydomonas reinhardtii*, *Plant J.* 94 (2018) 548–561, <https://doi.org/10.1111/tpj.13878>.
- [123] Y.S. Cheng, Y. Zheng, J. Labavitch, J. Vander Gheynst, Virus infection of *Chlorella variabilis* and enzymatic saccharification of algal biomass for bioethanol production, *Bioresour. Technol.* 137 (2013) 326–331, <https://doi.org/10.1016/j.biortech.2013.03.055>.
- [124] T. Maswana, P. Lindblad, C. Maneeruttanarungroj, Improved biohydrogen production by immobilized cells of the green alga *Tetraspora* sp. CU2551 incubated under aerobic condition, *J. Appl. Phycol.* 32 (2020) 2937–2945, <https://doi.org/10.1016/j.biombioe.2018.01.005>.
- [125] S.N. Kosourov, M. Seibert, Hydrogen photoproduction by nutrient-deprived *Chlamydomonas reinhardtii* cells immobilized within thin alginate films under aerobic and anaerobic conditions, *Biotechnol. Bioeng.* 102 (2009) 50–58, <https://doi.org/10.1002/bt.22050>.
- [126] E. Touloupakis, C. Faraloni, A.M.S. Benavides, J. Masojídek, G. Torzillo, Sustained photobiological hydrogen production by *Chlorella vulgaris* without nutrient starvation, *Int. J. Hydrog. Energy* 46 (2021) 3684–3694, <https://doi.org/10.1016/j.ijhydene.2021.12.127>.
- [127] S. Kosourov, M. Jokel, E.M. Aro, Y. Allahverdiyeva, A new approach for sustained and efficient H₂ photoproduction by *Chlamydomonas reinhardtii*, *Energy Environ. Sci.* 11 (2018) 1431–1436, <https://doi.org/10.1039/c8ee00054a>.
- [128] N. Fakhimi, A. Dubini, O. Tavakoli, D. González-Ballester, Acetic acid is key for synergetic hydrogen production in *Chlamydomonas*-bacteria co-cultures, *Bioresour. Technol.* 289 (2019), 121648, <https://doi.org/10.1016/j.biortech.2019.121648>.
- [129] D. Stojkovic, G. Torzillo, C. Faraloni, M. Valant, Hydrogen production by sulfur deprived *ti* O₂-encapsulated *Chlamydomonas reinhardtii* cells, *Int. J. Hydrog. Energy* 40 (2015) 3201–3206, <https://doi.org/10.1016/j.ijhydene.2014.12.115>.
- [130] S. Oncel, F. Vardar-Sukan, Photo-bioproduction of hydrogen by *Chlamydomonas reinhardtii* using a semi-continuous process regime, *Int. J. Hydrog. Energy* 34 (2009) 7592–7602, <https://doi.org/10.1016/j.ijhydene.2009.07.027>.
- [131] N. Laokua, N. Rittiyani, Y. Kornrawudaphikasama, R. Klinsalee, Y. Tonawut, N. Preechaphonkul, W. Raksajit, W. Khetkorn, W. Dejitsakdi, C. Maneeruttanarungroj, Optimal conditions for maximized H₂ yield from a new green algal strain *Chlorella* sp. KLS61, *J. Appl. Phycol.* 34 (2022) 1909–1919, <https://doi.org/10.1007/s10811-022-02779-y>.
- [132] M.A. Javed, A.M. Zafar, A. Aly Hassan, Regulate oxygen concentration using a co-culture of activated sludge bacteria and *Chlorella vulgaris* to maximize biophotolytic hydrogen production, *Algal Res.* 63 (2022), 102649, <https://doi.org/10.1016/j.algal.2022.102649>.
- [133] T.Q. Shi, L.R. Wang, Z.X. Zhang, X.M. Sun, H. Huang, Stresses as first-line tools for enhancing lipid and carotenoid production in microalgae, *Front. Bioeng. Biotechnol.* 8 (2020) 610, <https://doi.org/10.3389/fbioe.2020.00610>.
- [134] V. Nagy, A. Podmaniczki, A. Vidal-Meireles, R. Tengölics, L. Kovács, G. Rákhely, A. Scoma, S.Z. Tóth, Water-splitting-based, sustainable and efficient H₂ production in green algae as achieved by substrate limitation of the Calvin–Benson–Bassham cycle, *Biotechnol. Biofuel* 11 (2018) 1–16, <https://doi.org/10.1186/s13068-018-1069-0>.
- [135] W. Ma, M. Chen, L. Wang, L. Wei, Q. Wang, Treatment with NaHSO₃ greatly enhances photobiological H₂ production in the green alga *Chlamydomonas reinhardtii*, *Bioresour. Technol.* 102 (2011) 8635–8638, <https://doi.org/10.1016/j.biortech.2011.03.052>.
- [136] O. Kruse, J. Rupprecht, K.P. Bader, S.T. Hall, P.M. Schenk, G. Finazzi, B. Hankamer, Improved photobiological H₂ production in engineered green algal cells, *J. Biol. Chem.* 280 (2005) 34170–34177, <https://doi.org/10.1074/jbc.M503840200>.
- [137] T.S. Pinto, F.X. Malcata, J.D. Arrabaça, J.M. Silva, R.J. Spreitzer, M.G. Esquivel, Rubisco mutants of *Chlamydomonas reinhardtii* enhance photosynthetic hydrogen production, *Appl. Microbiol. Biotechnol.* 97 (2013) 5635–5643, <https://doi.org/10.1007/s00253-013-4920-z>.
- [138] M. Schulz-Raffelt, V. Chochois, P. Auroy, S. Cuiné, E. Billon, D. Dauvillée, Y. L. Beisson, G. Peltier, Hyper-accumulation of starch and oil in a *Chlamydomonas* mutant affected in a plant-specific DYRK kinase, *Biotechnol. Biofuel* 8 (2016) 55, <https://doi.org/10.1186/s13068-016-0469-2>.
- [139] A. Baltz, K.V. Dang, G. Peltier, Plastidial expression of type II NAD(P)H dehydrogenase increases the reducing state of plastoquinones and hydrogen photoproduction rate by the indirect pathway in *Chlamydomonas reinhardtii*, *Plant Physiol.* 165 (2014) 1344–1352, <https://doi.org/10.1104/pp.114.240432>.
- [140] H. Eilenberg, I. Weiner, O. Ben-Zvi, The dual effect of a ferredoxin-hydrogenase fusion protein in vivo: successful divergence of the photosynthetic electron flux towards hydrogen production and elevated oxygen tolerance, *Biotechnol. Biofuels* 9 (2016) 182, <https://doi.org/10.1186/s13068-016-0601-3>.
- [141] A.M. Lakanieni, C.J. Hularr, O.H. Tuovinen, D.N. Thomas, Biogenic hydrogen and methane production from *Chlorella vulgaris* and *Dunaliella tertiolecta* biomass, *Biotechnol. Biofuels* 4 (2011) 34, <https://doi.org/10.1186/1754-6834-4-34>.
- [142] P.S. Ferreira, A. Shamsuzzoha, P. Cunha, Framework for performance measurement and management in a collaborative business environment, *Int. J. Product. Perform. Manag.* 61 (2012) 672–690, <https://doi.org/10.1108/17410401211249210>.
- [143] Z. Honarmandrad, K. Kucharska, J. Gebicki, Processing of biomass prior to hydrogen fermentation and post-fermentative broth management, *Molecules* 27 (2022) 7658, <https://doi.org/10.3390/molecules27217658>.
- [144] J. Wang, Y. Yin, Fermentative hydrogen production using pretreated microalgal biomass as feedstock, *Microb. Cell Factories* 17 (2018) 22, <https://doi.org/10.1186/s12934-018-0871-5>.
- [145] K. Bolatkhan, A.K. Sadvakasova, B.K. Zayadan, A.B. Kakimova, F.K. Sarsekeyeva, B.D. Kossalbayev, A.M. Bozieva, S. Alwasel, S.I. Allakhverdiev, Prospects for the creation of a waste-free technology for wastewater treatment and utilization of carbon dioxide based on cyanobacteria for biodiesel production, *J. Biotechnol.* 324 (2020) 162–170, <https://doi.org/10.1016/j.jbiotec.2020.10.010>.
- [146] G.K. Kamshybayeva, B.D. Kossalbayev, A.K. Sadvakasova, B.K. Zayadan, A.M. Bozieva, D. Dunikov, S. Alwasel, S.I. Allakhverdiev, Strategies and economic feasibilities in cyanobacterial hydrogen production, *Int. J. Hydrog. Energy* 47 (2022) 29661–29684, <https://doi.org/10.1016/j.ijhydene.2022.06.277>.
- [147] M.A. Brown, P. Dwivedi, S. Mani, D. Matisoff, J.E. Mohan, J. Mullen, M. Oxman, M. Rodgers, R. Simmons, B. Beasley, L. Polepeddi, A framework for localizing global climate solutions and their carbon reduction potential, *Proc. Natl. Acad. Sci.* 118 (2021), e210008118, <https://doi.org/10.1073/pnas.2100081118>.
- [148] C. Dinca, C. Marculescu, A. Badea, C. Gheorghe, Critical analysis of GHG emissions generate by the fossil fuel power plant, in: *Mathematical Methods, Computational Techniques, Non-linear Systems, Intelligent Systems*, 2008, ISBN 978-960-474-012-3, pp. 408–413.

- [149] R.M. Gounder, R.M. Gounder, Processing of Heavy Crude Oils - Challenges and Opportunities, 2019, <https://doi.org/10.5772/intechopen.74912>.
- [150] A.M. Culloch, A.A. Lindley, Global emissions of HFC-23 estimated to year 2015, *Atmos. Environ.* 41 (2007) 1560–1566, <https://doi.org/10.1016/j.atmosenv.2006.02.021>.
- [151] G. Coppola, M.T. Gaudio, C.G. Lopresto, V. Calabro, S. Curcio, S. Chakraborty, Bioplastic from renewable biomass: a facile solution for a greener environment, *Earth Syst. Environ.* 5 (2021) 231–251, <https://doi.org/10.1007/s41748-021-00208-7>.
- [152] J.W. Roy Chong, X. Tan, K.S. Khoo, H.S. Ng, W. Jonglertjunya, G.Y. Yew, P. L. Show, Microalgae-based bioplastics: future solution towards mitigation of plastic wastes, *Environ. Res.* 206 (2022), 112620, <https://doi.org/10.1016/j.envres.2021.112620>.
- [153] M.A. Zeller, R. Hunt, A. Jones, S. Sharma, Bioplastics and their thermoplastic blends from *Spirulina* and *Chlorella* microalgae, *J. Appl. Polym. Sci.* 130 (2013) 3263–3275, <https://doi.org/10.1002/app.39559>.
- [154] G. Coppola, M.T. Gaudio, C.G. Lopresto, V. Calabro, S. Curcio, S. Chakraborty, Bioplastic from renewable biomass: a facile solution for a greener environment, *Earth Syst. Environ.* 5 (2021) 231–251, <https://doi.org/10.1007/s41748-021-00208-7>.
- [155] B.D. Beckstrom, M.H. Wilson, M. Crocker, J.C. Quinn, Bioplastic feedstock production from microalgae with fuel co-products: a techno-economic and life cycle impact assessment, *Algal Res.* 46 (2020), 101769, <https://doi.org/10.1016/j.algal.2019.101769>.
- [156] F. Hempel, A.S. Bozarth, N. Lindenkamp, A. Klingl, S. Zauner, U. Linne, A. Steinbüchel, U.G. Maier, Microalgae as bioreactors for bioplastic production, *Microb. Cell Factories* 10 (2011) 81, <https://doi.org/10.1186/1475-2859-10-81>.
- [157] S. Venkata Mohan, M. Hemalatha, D. Chakraborty, S. Chatterjee, P. Ranadheer, R. Kona, Algal biorefinery models with self-sustainable closed loop approach: trends and prospective for blue-bioeconomy, *Bioresour. Technol.* 295 (2020), 122128, <https://doi.org/10.1016/j.biortech.2019.122128>.
- [158] S. Onen Cinar, Z.K. Chong, M.A. Kucuker, N. Wiczorek, U. Cengiz, K. Kuchta, Bioplastic production from microalgae: a review, *Int. J. Environ. Res. Public Health* 17 (2020) 3842, <https://doi.org/10.3390/ijerph17113842>.
- [159] J.W. Chong, X. Tan, K.S. Khoo, H.S. Ng, W. Jonglertjunya, G.Y. Yew, P.L. Show, Microalgae-based bioplastics: future solution towards mitigation of plastic wastes, *Environ. Res.* 206 (2022), 112620, <https://doi.org/10.1016/j.envres.2021.112620>.
- [160] M. Carlsson, I. Naroznova, J. Möller, C. Scheutz, A. Lagerkvist, Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems, *Resour. Conserv. Recycl.* 102 (2015) 58–66, <https://doi.org/10.1016/j.resconrec.2015.06.012>.
- [161] M. Gozan, C. Noviasari, The effect of glycerol addition as plasticizer in *Spirulina platensis* based bioplastic, *E3S Web Conf.* 67 (2018) 03048, <https://doi.org/10.1051/e3sconf/20186703048>.
- [162] S.M. Abdo, G.H. Ali, Analysis of polyhydroxybutyrate and bioplastic production from microalgae, *Bull. Natl. Res. Cent.* 43 (2019) 97, <https://doi.org/10.1186/s42269-019-0135-5>.
- [163] C. Mathiot, P. Ponge, B. Gallard, J.F. Sassi, F. Delrue, N. Le Moigne, Microalgae starch-based bioplastics: screening of ten strains and plasticization of unfractionated microalgae by extrusion, *Carbohydr. Polym.* 208 (2019) 142–151, <https://doi.org/10.1016/j.carbpol.2018.12.057>.
- [164] H.A. Sabathini, L. Windiani, M. Gozan Dianursanti, Mechanical physical properties of chlorella-PVA based bioplastic with ultrasonic homogenizer, *E3S Web Conf.* 67 (2018) 03046, <https://doi.org/10.1051/e3sconf/20186703046>.
- [165] G. Kavitha, C. Kurinjimalar, K. Sivakumar, M. Kaarthik, R. Aravind, P. Palani, et al., Optimization of polyhydroxybutyrate production utilizing waste water as nutrient source by *Botryococcus braunii* Kütz using response surface methodology, *Int. J. Biol. Macromol.* 93 (2016) 534–542, <https://pubs.acs.org/doi/10.1016/j.ijbiomac.2016.09.019>.
- [166] S.K. Das, A. Sathish, J. Stanley, Production of biofuel and bioplastic from *Chlorella pyrenoidosa*, *Mater. Today Proc.* 5 (8) (2018) 16774–16781, <https://pubs.acs.org/doi/10.1016/j.matpr.2018.06.020>.
- [167] H.V. de Mendonça, P. Assemany, M. Abreu, E. Couto, A.M. Maciel, R.L. Duarte, M. G.B. dos Santos, A. Reis, Microalgae in a global world: new solutions for old problems? *Renew. Energy* 165 (2021) 842–862, <https://doi.org/10.1016/j.renene.2020.11.014>.
- [168] T.M. Letcher, The Impacts of Climate Change, Elsevier, 2021, <https://doi.org/10.1016/C2019-0-04893-5>.
- [169] Chandind, R. Kumar, R. Kumar, O. Prakash, The Impact of Chemical Fertilizers on Our Environment and Ecosystem, *Research Trends in Environmental Sciences*, 2019 (Accessed on 19 November 2022), <https://www.researchgate.net/publication/331132826>.
- [170] N. Bisht, P.S. Chauhan, Excessive and Disproportionate Use of Chemicals Cause Soil Contamination and Nutritional Stress, *Soil Contamination - Threats and Sustainable Solutions*, Intech. Open, 2020, <https://doi.org/10.5772/intechopen.94593>.
- [171] S. Kumar, S.S. Diksha, R. Kumar Sindhu, Biofertilizers: an ecofriendly technology for nutrient recycling and environmental sustainability, *Curr. Res. Microbial Sci.* 3 (2022), 100094, <https://doi.org/10.1016/j.crmicr.2021.100094>.
- [172] S. Guo, P. Wang, X. Wang, M. Zou, Microalgae as biofertilizer in modern agriculture, in: M. Alam, J.L. Xu, Z. Wang (Eds.), *Microalgae Biotechnology for Food, Health and High Value Products*, Springer, Singapore, 2020, pp. 397–411, https://doi.org/10.1007/978-981-15-0169-2_12.
- [173] I. Priyadarshani, B. Rath, Commercial and industrial applications of micro algae – a review, *J. Algal Biomass Util.* 3 (2012) 89–100. ISSN: 2229- 6905.
- [174] M.J. Van Oosten, O. Pepe, S. De Pascale, S. Silletti, A. Maggio, The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants, *Chem. Biol. Technol. Agric.* 4 (2017) 5, <https://doi.org/10.1186/s40538-017-0089-5>.
- [175] D. Chittora, M. Meena, T. Barupal, P. Swapnil, K. Sharma, Cyanobacteria as a source of biofertilizers for sustainable agriculture, *Biochem. Biophys. Rep.* 22 (2020), 100737, <https://doi.org/10.1016/j.bbrep.2020.100737>.
- [176] M.O. Bauenova, A.K. Sadvakasova, Z.O. Mustapayeva, M. Kokociński, B. K. Zayadan, M.K. Wojciechowicz, N.R. Akmuhanova, S. Alwasel, S. I. Allakhverdiev, Potential of microalgae *Parachlorella kessleri* Bh-2 as bioremediation agent of heavy metals cadmium and chromium, *Algal Res.* 59 (2021), 102463, <https://doi.org/10.1016/j.algal.2021.102463>.
- [177] N.R. Akmuhanova, A.K. Sadvakasova, K. Bolatkhani, B.K. Zayadan, M. O. Bauenova, Consortium of higher aquatic plants and microalgae designed to purify sewage of heavy metal ions, *Russ. J. Plant Physiol.* 65 (2018) 143–149, <https://doi.org/10.1134/S1021443718010028>.
- [178] B.K. Zayadan, A.K. Sadvakasova, D.N. Matorin, N.R. Akmuhanova, M. Kokociński, N.P. Timofeev, K. Balouch, M.O. Bauenova, Effect of cadmium ions on some biophysical parameters and ultrastructure of *Ankistrodesmus* sp. B-11 cells, *Russ. J. Plant Physiol.* 67 (2020) 845–854, <https://doi.org/10.1134/S1021443720040196>.
- [179] W.A. Stirk, P. Bálint, D. Tarkowska, O. Novák, M. Strnad, V. Ördög, J. van Staden, Hormone profiles in microalgae: gibberellins and brassinosteroids, *Plant Physiol. Biochem.* 70 (2013) 348–353, <https://doi.org/10.1016/j.plaphy.2013.05.037>.
- [180] K.O. Romanenko, I.V. Kosakovskaya, P.O. Romanenko, Phytohormones of microalgae: biological role and involvement in the regulation of physiological processes, *IJA* 18 (2016), <https://doi.org/10.1615/InterJAlgae.v18.i2.70>.
- [181] S. Ha, R. Vankova, K. Yamaguchi-Shinozaki, K. Shinozaki, L.S.P. Tran, Cytokinin: metabolism and function in plant adaptation to environmental stresses, *Trends Plant Sci.* 17 (2012) 172–179, <https://doi.org/10.1016/j.tplants.2011.12.005>.
- [182] V.M. Sponsel, P. Hedden, Gibberellin biosynthesis and inactivation, in: P.J. Davies (Ed.), *Plant Hormones: Biosynthesis, Signal Transduction, Action*, Springer Netherlands, Dordrecht, 2010, pp. 63–94, https://doi.org/10.1007/978-1-4020-2686-7_4.
- [183] V. Barone, A. Baglieri, P. Stevanato, C. Broccanello, G. Bertoldo, M. Bertaggia, M. Cagnin, D. Pizzeghello, V.M.C. Moliterni, G. Mandolino, F. Fornasier, A. Squartini, S. Nardi, G. Concheri, Root morphological and molecular responses induced by microalgae extracts in sugar beet (*Beta vulgaris* L.), *J. Appl. Phycol.* 30 (2018) 1061–1071, <https://doi.org/10.1007/s10811-017-1283-3>.
- [184] F. Faheed, Z. Fattah, Effect of *Chlorella vulgaris* as bio-fertilizer on growth parameters and metabolic aspects of lettuce plant, *J. Agric. Soc. Sci.* 4 (2008) 165–169.
- [185] S.C. Wuang, M.C. Khin, P.Q.D. Chua, Y.D. Luo, Use of *Spirulina* biomass produced from treatment of aquaculture wastewater as agricultural fertilizers, *Algal Res.* 15 (2016) 59–64, <https://doi.org/10.1016/j.algal.2016.02.009>.
- [186] J. Garcia-Gonzalez, M. Sommerfeld, Biofertilizer and biostimulant properties of the microalgae *Acutodesmus dimorphus*, *J. Appl. Phycol.* 28 (2016) 1051–1061, <https://doi.org/10.1007/s10811-015-0625-2>.
- [187] H. El Arroussi, R. Benhima, A. Elbaouchi, B. Sijilmassi, N. El Mernissi, A. Aafsar, I. Meftah-Kadmiri, N. Bendaou, A. Smouni, Dunaliella salina exopolysaccharides: a promising biostimulant for salt stress tolerance in tomato (*Solanum lycopersicum*), *J. Appl. Phycol.* 30 (2018) 2929–2941, <https://doi.org/10.1007/s10811-017-1382-1>.
- [188] H.H. Abd El-Baky, F.K. El-Baz, G.S. El Baroty, Enhancing antioxidant availability in wheat grains from plants grown under seawater stress in response to microalgae extract treatments, *J. Sci. Food Agric.* (2010) 299–303, <https://doi.org/10.1002/jsfa.3815>.
- [189] N. Renuka, A. Guldhe, R. Prasanna, P. Singh, F. Bux, Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges, *Biotechnol. Adv.* 36 (2018) 1255–1273, <https://doi.org/10.1016/j.biotechadv.2018.04.004>.
- [190] R. Xiao, Y. Zheng, Overview of microalgal extracellular polymeric substances (EPS) and their applications, *Biotechnol. Adv.* 34 (2016) 1225–1244, <https://doi.org/10.1016/j.biotechadv.2016.08.004>.
- [191] J.S. Castro, M.L. Calijuri, J. Ferreira, P.P. Assemany, V.J. Ribeiro, Microalgae based biofertilizer: a life cycle approach, *Sci. Total Environ.* 724 (2020), 138138, <https://doi.org/10.1016/j.scitotenv.2020.138138>.
- [192] E. Ibañez, A. Cifuentes, Benefits of using algae as natural sources of functional ingredients, *J. Sci. Food Agric.* 93 (2013) 703–709, <https://doi.org/10.1002/jsfa.6023>.
- [193] G. Markou, E. Nerantzis, Microalgae for high-value compounds and biofuels production: a review with focus on cultivation under stress conditions, *Biotechnol. Adv.* 31 (2013) 1532–1542, <https://doi.org/10.1016/j.biotechadv.2013.07.011>.
- [194] L. Li, W. Li, Y.H. Kim, Y.W. Lee, *Chlorella vulgaris* extract ameliorates carbon tetrachloride-induced acute hepatic injury in mice, *Exp. Toxicol. Pathol.* 65 (2013) 73–80, <https://doi.org/10.1016/j.etp.2011.06.003>.
- [195] M.E.A. El-Hacka, S. Abdelnour, M. Alagawanya, M. Abdo, M.A. Sakrd, A. F. Khafage, S.A. Mahgoub, S.S. Elensrg, M.G. Gebrie, Microalgae in modern cancer therapy: current knowledge, *Biomed. Pharmacother.* 111 (2019) 42–50, <https://doi.org/10.1016/j.biopha.2018.12.069>.
- [196] T. Chang, S. Ohta, N. Ikegami, H. Miyata, T. Kashimoto, M. Kondo, Antibiotic substances produced by a marine green alga, *Dunaliella primolecta*, *Bioresour. Technol.* 44 (1993) 149–153, [https://doi.org/10.1016/0960-8524\(93\)90189-1](https://doi.org/10.1016/0960-8524(93)90189-1).
- [197] F.F. Madkour, M.M. Abdel-Daim, Hepatoprotective and antioxidant activity of *Dunaliella salina* in paracetamol-induced acute toxicity in rats, *Indian J. Pharm. Sci.* 75 (2013) 642–648. PMID: PMC3928727.

- [198] R.K. Saini, Y.S. Keum, Carotenoid extraction methods: a review of recent developments, *Food Chem.* 240 (2018) 90–103, <https://doi.org/10.1016/j.foodchem.2017.07.099>.
- [199] R.P. Rastogi, S.P. Singh, D.P. Häder, R.P. Sinha, Detection of reactive oxygen species (ROS) by the oxidant-sensing probe 2',7'-dichlorodihydrofluorescein diacetate in the cyanobacterium *Anabaena variabilis* PCC 7937, *Biochem. Biophys. Res. Commun.* 397 (2010) 603–607, <https://doi.org/10.1016/j.bbrc.2010.06.006>.
- [200] M. Moo-Young, Supercritical fluid technology in bioseparation, in: E.D. Ramsey, W. Guo, J.Y. Liu, X.H. Wu (Eds.), *Comprehensive Biotechnology*, 3rd ed., Pergamon, Oxford, UK, 2019, pp. 713–724, <https://doi.org/10.1016/B978-0-444-64046-8.00122-1>.
- [201] M.M.R. Shah, Y. Liang, J.J. Cheng, M. Daroch, Astaxanthin-producing green microalga *haematococcus pluvialis*: from single cell to high value commercial products, *Front. Plant Sci.* 7 (2016) 531, <https://doi.org/10.3389/fpls.2016.00531>.
- [202] B. Stachowiak, P. Szulc, Astaxanthin for the food industry, *Molecules* 26 (2021) 2666, <https://doi.org/10.3390/molecules26092666>.
- [203] F. Daneshvar, H. Chen, K. Nohb, H.J. Sue, Critical challenges and advances in the carbon nanotube–metal interface for next-generation electronics, *Nanoscale Adv.* 3 (2021) 942–962, <https://doi.org/10.1039/D0NA00822B>.
- [204] C. Xu, N.G. McDowell, R.A. Fisher, L. Wei, S. Sevanto, B.O. Christoffersen, E. Weng, R.S. Middleton, Increasing impacts of extreme droughts on vegetation productivity under climate change, *Nat. Clim. Chang.* 9 (2019) 948–953, <https://doi.org/10.1038/s41558-019-0630-6>.
- [205] J. Li, L.N. Kang, Y.L. Qiao, Review of the cervical cancer disease burden in mainland China, *Asian Pac. J. Cancer Prev.* 12 (2011) 1149–1153. ID: 35451840.
- [206] M. Aboshatta, V.A. Magueijo, Comprehensive study of CO₂ absorption and desorption by choline-chloride/levulinic-acid-based deep eutectic solvents, *Molecules* 26 (2021) 5595, <https://doi.org/10.3390/molecules26185595>.
- [207] M.B. Haider, D. Jha, B.M. Sivagnanam, R. Kumar, Thermodynamic and kinetic studies of CO₂ capture by glycol and amine-based deep eutectic solvents, *J. Chem. Eng.* 63 (2018) 2671–2680, <https://doi.org/10.1021/acs.jced.8b00015>.
- [208] S. Bellou, M. Baeshen, A. Elazzazy, D. Aggeli, F. Sayegh, G. Aggelis, Microalgal lipids biochemistry and biotechnological perspectives, *Biotechnol. Adv.* 32 (2014) 1476–1493, <https://doi.org/10.1016/j.biotechadv.2014.10.003>.
- [209] Y.F. Niu, M.H. Zhang, D.W. Li, W.D. Yang, J.S. Liu, W.B. Bai, H.Y. Li, Improvement of neutral lipid and polyunsaturated fatty acid biosynthesis by overexpressing a type 2 diacylglycerol acyltransferase in marine diatom *Phaeodactylum tricornutum*, *Mar. Drugs* 11 (2013) 4558–4569, <https://doi.org/10.3390/md11114558>.
- [210] A. Klok, P. Lamers, D. Martens, R. Draaisma, R. Wijffels, Edible oils from microalgae: insights in TAG accumulation, *Trends Biotechnol.* 32 (2014) 521–528, <https://doi.org/10.1016/j.biombioe.2021.106108>.
- [211] S. Bellou, I.E. Triantaphyllidou, D. Aggeli, A.M. Elazzazy, M.N. Baeshen, G. Aggelis, Microbial oils as food additives: recent approaches for improving microbial oil production and its polyunsaturated fatty acid content, *Curr. Opin. Biotechnol.* 37 (2016) 24–35, <https://doi.org/10.1016/j.copbio.2015.09.005>.
- [212] X.D. Deng, B. Gu, Y.J. Li, X.W. Hu, J.C. Guo, X.W. Fei, The roles of acyl-CoA: diacylglycerol acyltransferase 2 genes in the biosynthesis of triacylglycerols by the green algae *Chlamydomonas reinhardtii*, *Mol. Plant* 5 (2012) 945–947, <https://doi.org/10.1093/mp/sss040>.
- [213] X. Wang, F. Zhang, L. Li, H. Zhang, S. Deng, Chapter seven – carbon dioxide capture, *Adv. Chem. Eng.* 58 (2021) 297–348, <https://doi.org/10.1016/bbs.ache.2021.10.005>.
- [214] J. Sing, D.W. Dhar, Overview of carbon capture technology: microalgal biorefinery concept and state-of-the-art, *Front. Mar. Sci.* 6 (2019) 29, <https://doi.org/10.3389/fmars.2019.00029>.
- [215] H. Onyeaka, T. Miri, K.C. Obileke, A. Hart, C. Anumudu, Z.T. Al-Sharif, Minimizing carbon footprint via microalgae as a biological capture, *Carbon Capt. Sci. Technol.* 1 (2021), 100007, <https://doi.org/10.1016/j.ccst.2021.100007>.
- [216] S. Lage, Z. Gojkovic, C. Funk, F.G. Gentili, Algal biomass from wastewater and flue gases as a source of bioenergy, *Energies* 11 (2018) 664, <https://doi.org/10.3390/en11030664>.
- [217] X. You, L. Yang, X. Zhou, Y. Zhang, Sustainability and carbon neutrality trends for microalgae-based wastewater treatment: a review, *Environ. Res.* 209 (2022), 112860, <https://doi.org/10.1016/j.envres.2022.112860>.
- [218] M. Yang, C. Xue, L. Li, Z. Gao, Q. Liu, P. Qian, J. Dong, K. Gao, Design and performance of a low-cost microalgae culturing system for growing *Chlorella sorokiniana* on cooking cocoon wastewater, *Algal Res.* 62 (2022), 102607, <https://doi.org/10.1016/j.algal.2021.102607>.
- [219] A. Aliyu, J.G.M. Lee, A.P. Harvey, Microalgae for biofuels via thermochemical conversion processes: a review of cultivation, harvesting and drying processes, and the associated opportunities for integrated production, *Bioresour. Technol. Rep.* 14 (2021), 100676, <https://doi.org/10.1016/j.biteb.2021.100676>.
- [220] S. Chinnassamy, A. Bhatnagar, R.W. Hunt, K.C. Das, Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications, *Bioresour. Technol.* 101 (2010) 3097–3105, <https://doi.org/10.1016/j.biortech.2009.12.026>.
- [221] J. Hu, H. Liu, P. Shukla, W. Lin, J. Luo, Nitrogen and phosphorus removals by the agar-immobilized *Chlorella saccharophila* with long-term preservation at room temperature, *Chemosphere* 251 (2020), 126406, <https://doi.org/10.1016/j.chemosphere.2020.126406>.
- [222] D.C. Murador, L.M. de Souza Mesquita, N. Vannuchi, A.R.C. Braga, V.V. de Rosso, Bioavailability and biological effects of bioactive compounds extracted with natural deep eutectic solvents and ionic liquids: advantages over conventional organic solvents, *Curr. Opin. Food Sci.* 26 (2019) 25–34, <https://doi.org/10.1016/j.cofs.2019.03.002>.
- [223] R. Chowdhury, F. Freire, Bioenergy production from algae using dairy manure as a nutrient source: life cycle energy and greenhouse gas emission analysis, *Appl. Energy* 154 (2015) 1112–1121, <https://doi.org/10.1016/j.apenergy.2015.05.045>.
- [224] G. Kumar, S. Shobana, W.H. Chen, Q.V. Bach, S.H. Kim, A.E. Atabani, A review of thermochemical conversion of microalgal biomass for biofuels: chemistry and processes, *Green Chem.* 19 (2017) 44–67, <https://doi.org/10.1039/c6gc01937d>.
- [225] R. Prasad, S.K. Gupta, N. Shabnam, C.Y.B. Oliveira, A.K. Nema, F.A. Ansari, F. Bux, Role of microalgae in global CO₂ sequestration: physiological mechanism, recent development, challenges, and future prospective, *Sustainability* 13 (2021) 13061, <https://doi.org/10.3390/su132313061>.
- [226] S. Viswanaathan, P.K. Perumal, S. Sundaram, Integrated approach for carbon sequestration and wastewater treatment using algal-bacterial consortia: opportunities and challenges, *Sustainability* 14 (2022) 1075, <https://doi.org/10.3390/su14031075>.
- [227] S. Ranjbar, F. Malcata, Challenges and prospects for sustainable microalga-based oil: a comprehensive review, with a focus on metabolic and genetic engineering, *Fuel* 324 (2022), 124567, <https://doi.org/10.1016/j.fuel.2022.124567>.
- [228] J. Poppa, Z. Lakner, M. Harangi-Rákosa, M. Fáric, The effect of bioenergy expansion: food, energy, and environment, *Renew. Sust. Energ. Rev.* 32 (2014) 559–578, <https://doi.org/10.1016/j.rser.2014.01.056>.
- [229] C.V. García Prieto, F.D. Ramos, V. Estrada, M.A. Villar, M.S. Diaz, Optimization of an integrated algae-based biorefinery for the production of biodiesel, astaxanthin and PHB, *Energy* 139 (2017) 1159–1172, <https://doi.org/10.1016/j.energy.2017.08.036>.
- [230] D. Puyol, D.J. Batstone, T. Hülsen, S. Astals, M. Peces, J.O. Krömer, Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects, *Front. Microbiol.* 7 (2017) 2106, <https://doi.org/10.3389/fmicb.2016.02106>.