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Microalgal Carbon Dioxide (CO_2) Capture and Utilization from the European Union Perspective

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Abstract: The increasing concentration of anthropogenic CO_2 in the atmosphere is causing a global environmental crisis, forcing significant reductions in emissions. Among the existing CO_2 capture technologies, microalgae-guided sequestration is seen as one of the more promising and sustainable solutions. The present review article compares CO_2 emissions in the EU with other global economies, and outlines EU's climate policy together with current and proposed EU climate regulations. Furthermore, it summarizes the current state of knowledge on controlled microalgal cultures, indicates the importance of CO_2 phycoremediation methods, and assesses the importance of microalgae-based systems for long-term storage and utilization of CO_2. It also outlines how far microalgae technologies within the EU have developed on the quantitative and technological levels, together with prospects for future development. The literature overview has shown that large-scale take-up of technological solutions for the production and use of microalgal biomass is hampered by economic, technological, and legal barriers. Unsuitable climate conditions are an additional impediment, forcing operators to implement technologies that maintain appropriate temperature and lighting conditions in photobioreactors, considerably driving up the associated investment and operational costs.

Keywords: carbon dioxide emission; CO_2 capture; biosequestration; microalgae; long-term utilization; phycoremediation; fit for 55

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1. Introduction

Extensive carbon dioxide (CO_2) emissions into the atmosphere have created an environmental crisis and are considered the main driver of global warming [1]. Almost 65% of greenhouse gas (GHG) emissions are accounted to CO_2. Addressing the impacts of global warming has become a pressing concern for both economic systems and environmental/energy regulations in recent years [2]. Climate and ecological disasters have posed threats to humanity and thus forced decision-makers, politicians, and companies to significantly reduce anthropogenic GHG emissions into the atmosphere, with particular focus on CO_2. European Union (EU) nations have taken decisive and unwavering steps, consistently executing robust plans towards becoming carbon neutral in 2050 [3].

It is widely acknowledged that GHGs play a positive role by stabilizing temperature at an equilibrium beneficial for natural ecosystems. However, increasing net CO_2 in the air by long-term intensive combustion of fossil fuels causes global temperatures to rise uncontrollably and to an excessive degree. Climate change is currently treated as a key issue to be tackled, as it is considered a global threat to civilization [4]. Numerous papers have shown that increased levels of atmospheric CO_2 are detrimental to economic and agricultural development, water regimes, tourism, food production, and other branches of the economy [5].

Given the above, new technologies need to be developed to reduce CO_2 emissions into the atmosphere. This can be achieved by utilizing conventional methods based on low-emission or zero-emission technologies for fuel and energy production and use [6]. Another avenue is to develop and deploy effective methods of CO_2 sequestration. This refers to all processes designed for the purpose of capture, separation, transport and long-term storage of CO_2 in a suitable and safe location. Depending on the stage of the process, sequestration methods can be divided into direct and indirect ones. Direct sequestration aims to capture CO_2 before it is released into the atmosphere, then transport it to where it can be stored or re-used. Indirect sequestration serves to reduce CO_2 emission, i.e., binding of gases previously released into the atmosphere. CO_2-absorbing plants can be used for this purpose, for example, by phycoremediation techniques. Atmospheric CO_2 can also be fixed in the soil [7]

Mineral sequestration, referred to as mineral carbonation, is one of the most extensively explored direct methods. The technology involves the production of stable carbonate compounds by reacting CO_2 with artificially produced substances, naturally occurring substances in the environment, or other compounds (including waste) [8]. Solutions are sought to improve the performance and cost-effectiveness of mineral carbonation [9]. Despite its many advantages—such as safe and long-term binding of CO_2, as well as the sorption capacity of the materials—its potential for wide exploitation is hampered by the high operation and investment costs, the costs of acquiring and storing the minerals, the limited availability of effective adsorbents, and the technological complexity of the process. One of the most well-explored methods of storing CO_2 is sequestration in geological formations, which has attracted attention due to its capacity to store large amounts of gas and the gas accumulation time [10]. This concept calls for storing CO_2 in deep permeable formations covered by impermeable layers. The underground sites most commonly cited as suitable for storing CO_2 are: deep aquifers, productive or depleted oil/gas reservoirs, and unused coal deposits. Other commercially- and technologically-viable approaches to capturing and removing CO_2 from flue gas include physical processes (adsorption, membrane separation), chemical processes (adsorption and chemical absorption), and biological processes (forest plantation, ocean fertilization and using photosynthesizing microorganisms) [11]. A basic division of the methods used for binding CO_2 is presented in Figure 1.

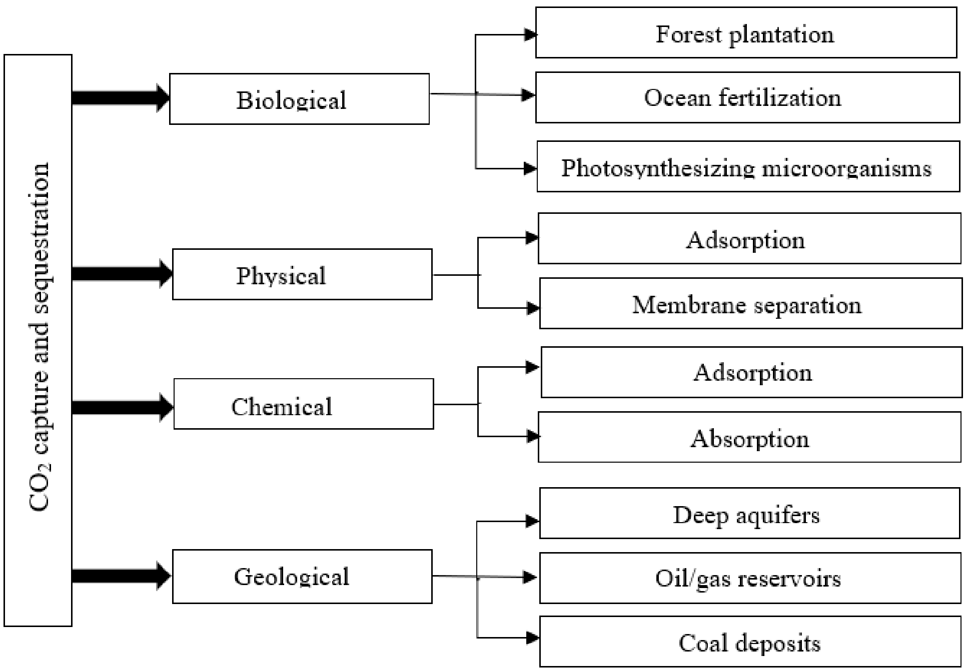


Figure 1. Classification of CO_2 capture and sequestration methods.

Out of the myriad available options, microalgae-mediated biosequestration is considered to be a promising solution that could help reduce atmospheric CO_2 emissions. The particular properties of microalgae—specifically, their extremely efficient utilization of solar energy and rapid growth of biomass—mean that microalgal biomass production systems offer considerable technological performance. Figure 2 presents a diagram of the biochemical conversion routes that transport CO_2 into microalgal biomass structures [12]. Bioreactors can harness anthropogenic waste produced by industrial and domestic sources [13]. This enables commercial systems of microalgae biomass production to be established on land unsuitable for agricultural use, near heating/cogeneration plants, sewage treatment plants and other industrial facilities that produce carbon dioxide and biogenic compounds.

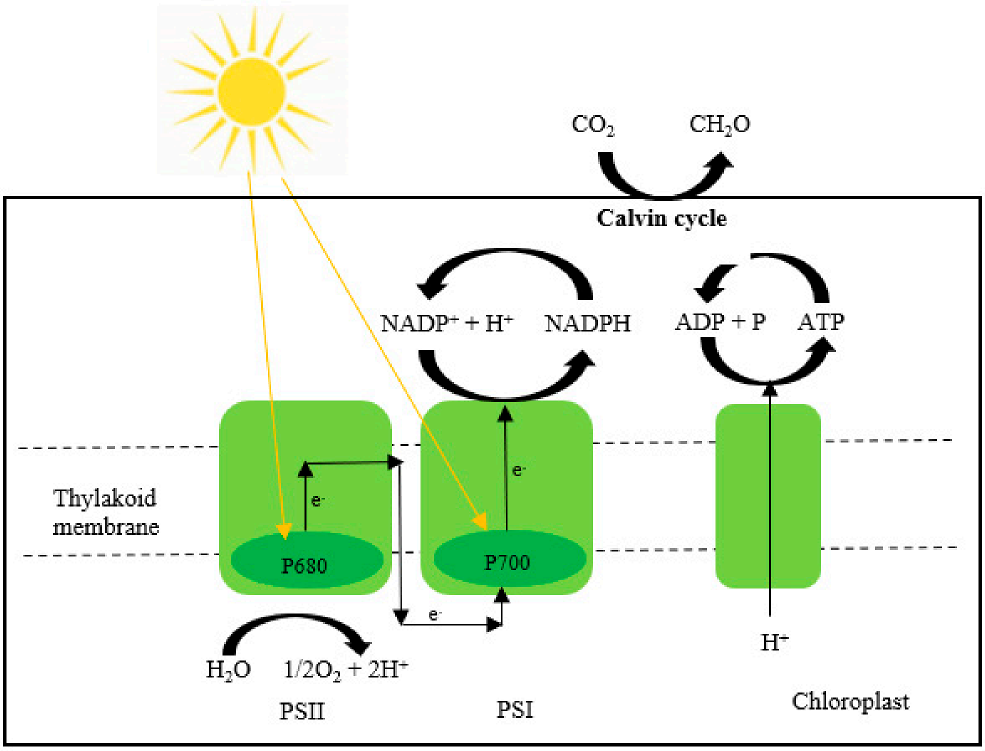


Figure 2. Mechanism of microalgal CO_2 sequestration via photosynthesis [12].

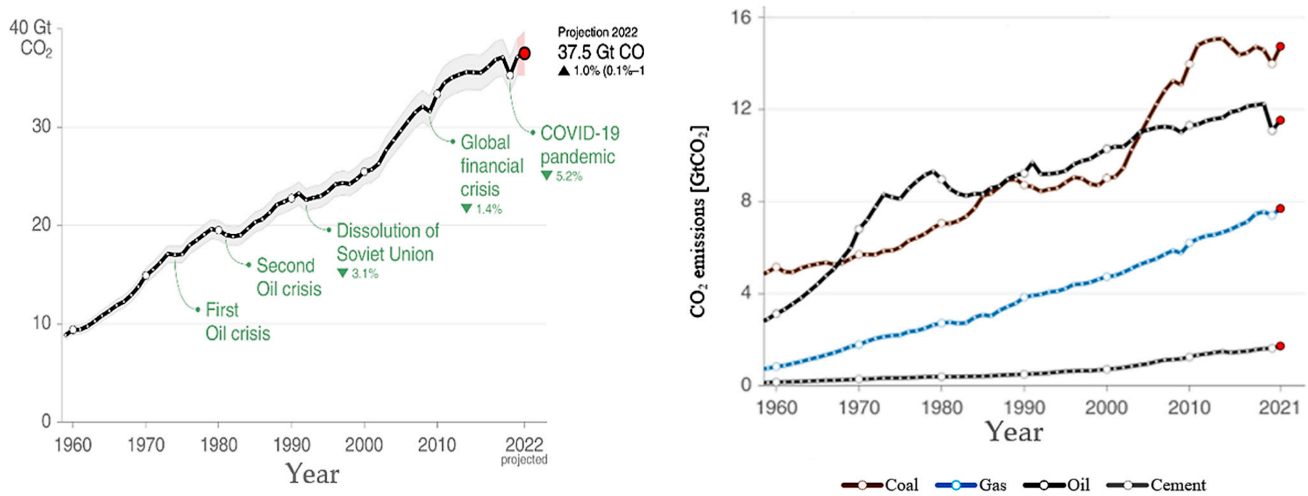
Successful implementation of methods for the capture and utilization of CO_2 requires not only that productive and cost-effective technologies be developed, but also that international agreements and pursuant emission limits/regulations be put in place [14]. The EU countries are currently undertaking bold and forward-looking actions in this respect, including with regard to circular economy, the Fit for 55 package, and the Green Deal [15]. The European Commission (the EC) has put forward a set of legislative proposals designed to align EU legislation, with its new greenhouse gas emission targets, with emissions to be reduced by at least 55% by 2030 (relative to 1990 levels). This package of proposals forms part of the European Green Deal, which aims to make Europe the first carbon-neutral continent by 2050. It should also be noted that the Climate Law adopted by the European Parliament in April 2021 requires that objectives be defined for 2040. This means that the Fit for 55 package is only one step towards neutrality, and that new regulatory packages can be expected in the second half of the decade [16].

The aim of this paper is to present and analyze current knowledge on the feasibility of technologies for CO_2 capture and biosequestration using microalgae biomass. A literature review was conducted to compare CO_2 emission levels of EU countries with other global economies, to present current and proposed CO_2 regulations in the EU, to present an overview of technologies for producing microalgae biomass under controlled conditions, to define their applicability for reducing emissions in the EU, to discuss the importance of

CO_2 phycoremediation methods, and to assess the importance of microalgae-based systems for long-term storage and utilization of CO_2. The paper also identifies existing limitations and barriers to the successful implementation of microalgal technologies across the EU countries.

2. Global and EU Trends in CO_2 Emissions

According to analyses and statistics from the International Energy Agency, energy demand fell by 4% in 2020, whereas CO_2 emissions (which are tied to energy production) decreased by an estimated 5.8% [17]. Though this represents the largest percentage reduction since World War II, it should be considered a short-term anomaly in the long-standing upward trend in emissions [18]. The decline is directly attributable to the economic slowdown observed in many sectors, caused by restrictions imposed in response to the SARS-CoV-2 pandemic. The most pronounced decrease was observed in developed countries (up to 10%), whereas developing countries showed less of a reduction (approx. 4%). China, the world's largest emitter, was the only country to increase its CO_2 output [19]. Global fossil CO_2 emissions are given in Figure 3a [20], whereas CO_2 emission levels by source of fuel are presented in Figure 3b [20].



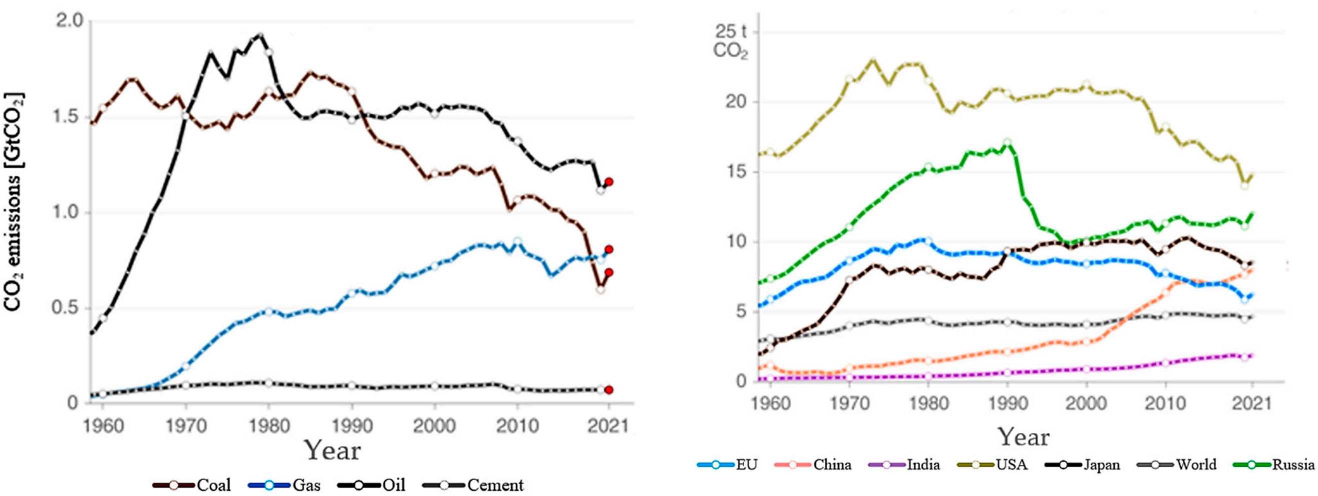
(**a**) (**b**)

Figure 3. Emissions of CO_2 from fossil fuels from 1960 to 2021: (**a**) global, (**b**) by source of fuel [20].

CO_2 emissions by China were 4% larger in 2021 compared to 2020 and 5.5% larger than in 2019, reaching 11.1 billion tons of CO_2 released. This translates to a 31% share in global emissions [20]. In turn, the USA produced 5.1 billion tons CO_2 in 2021, which accounts for 14% of global emissions, whereas India released 2.7 billion tons CO_2 in 2021—12.6% higher than in 2020, but 4.4% lower than in 2019, which makes it account for approx. 7% of the global emissions [20].

Coal and gas consumption in the global economy is rapidly growing as a result of stimulus packages driving consumption, as well as the shift from spending on services in favor of industrial goods. The SARS-CoV-2 pandemic and the global lockdown caused societies to stop their spending on leisure and tourism sectors, instead focusing on material goods [21]. If the global consumption of coal keeps rising at its current, rapid pace, the resultant CO_2 emissions will most likely exceed their 2014 peak. Recent oil consumption was relatively low, mainly due to the ongoing restrictions on travels [22]. However, CO_2 emissions from oil operations are expected to rise by 4.4% this year; though, taking into account the earlier decline in 2020, they will still be 6% lower than the 2019 level [20].

Emissions in the 27 EU Member States were 7.6% higher than those in 2020, but 4.2% lower than in 2019, at 2.8 billion tons CO_2. As such, the EU's share in global emissions is currently 7%. The whole continent of Europe produced 5571.28 Mt of fossil fuel CO_2, which accounts for 14.65% of global emissions [23]. Out of that, the 27 European Union countries and the United Kingdom produced 3303.97 Mt (8.69% global share). The largest emitters are: Russia (1792 Mt), Germany (702 Mt), the United Kingdom (364 Mt), Italy and San Marino (331 Mt), Poland (317 Mt), France and Monaco (314 Mt), Spain and Andorra (259 Mt), and Ukraine (196 Mt). Eurostat estimates indicate that CO_2 emissions fell across all of the Member States in 2020, with the average rate of decline being approx. 10%. The most significant drop was noted for Greece (−18.7%), followed by Estonia (−18.1%), Luxembourg (−17.9%), Spain (−16.2%), and Denmark (−14.8%). Conversely, the reduction was the least pronounced for Malta (−1.0%), Hungary (−1.7%) as well as Ireland and Lithuania (−2.6% each) [24]. Nevertheless, these reductions were only temporary and stemmed from the economic downturn caused by the SARS-CoV-2 pandemic. Germany's CO_2 output rebounded in 2021, rising by 33 billion tons compared to 2020 and reaching 772 billion tons. The 2021 increase in CO_2 was in large part driven by the economic recovery, which has radically pushed up the prices of various energy carriers [25]. The share of renewables was also relatively low, mainly due to the relatively windless weather. As such, the fossil fuel share in electricity production was larger than in 2020. These trends favored lignite/brown coal in particular (which has tremendous environmental impact), even despite the higher prices of emission allowances bought by power plant operators in 2021. The levels of emissions for fossil fuel combustion and cement production in the EU are presented in Figure 4a [20]. There has been a clear long-term pattern of reducing the consumption of oil and coal in favor of natural gas.



(**a**) (**b**)

Figure 4. Emissions of CO_2 from cement and fossil fuels from 1960 to 2021 (**a**) in the EU, (**b**) per capita CO_2 by countries [20].

Any comprehensive and objective assessment of CO_2 emissions must take into account their per capita levels. The United States is the leader in this category, despite the downward trend in the last 20 years. China has recently caught up to and overtaken the EU (Figure 4b) [20]. India's per capita emissions are still only a fraction of those generated by industrialized countries [26].

3. Current and Proposed EU Regulations

Under the Kyoto Protocol on climate change, which was concluded in December 1997, the European Union is committed to reduce its greenhouse gas emissions by 8% compared with the 1990 levels in the period 2008 to 2012. For the second commitment period of the Kyoto Protocol (2013 to 2020), the emissions are to be cut even further—a 20% reduction by 2020 (relative to 1990 levels). In the fourth phase of the EU ETS system (2021 to 2030), the EU intends to cut emissions by no less than 40% by 2030, in accordance with the 2015

Paris Agreement on Climate Change [27]. To that end, EU has set up a scheme for trading greenhouse gas emission allowances. Each emission allowance equals 1 ton of CO_2 or CO_2 equivalent within a given period [28].

One of the fundamental legal acts forming the basis of the current EU CO_2 emission trading scheme is Directive 2003/87/EC of 13 October 2003, amending the earlier Directive 96/61/EC of 24 September 1996, concerning integrated pollution prevention and control [29]. The prevailing greenhouse gas emission trading scheme (EU ETS) is the first and largest international scheme, covering almost 11,000 power plants and factories in 28 EU Member States plus Iceland, Norway, and Liechtenstein. It also regulates emissions generated by the aviation sector. This legal act forms the basis of EU's climate change mitigation policy and aims to control CO_2 emissions in a cost-effective and economically-efficient manner. The limits are set for the total quantity of a given greenhouse gas that can be emitted by the factories, power plants and other facilities covered by the scheme [30]. The applicable limits are systematically reduced in order to reduce total CO_2 emissions. The scheme allows emission allowances to be traded in a way which ensures that the total amount of emissions from industrial plants and aviation operations does not exceed the limit, and which will pave the way for the most effective emission mitigation measures.

The EU's new climate package is called 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. On 14 July 2021, the European Commission adopted a package of legislative proposals seeking to amend EU climate, energy, land use, transport and taxation policies to reduce net greenhouse gas emissions by no less than 55% by 2030—relative to 1990 levels [31]. Under the package, 57% of the allowances are to be sold on auctions from 2021 onward. At least half of the revenues collected by EU countries must be allocated towards climate-related objectives. Operators who failed to purchase sufficient allowances must pay penalties of EUR 100 per each ton of CO_2 released. The package's horizontal objective is to make Europe the first carbon-neutral continent by 2050 and implement the European Green Deal. The drafts submitted by the Commission are intended to provide legislative tools to achieve the goals of European Climate Law and to push the transition of the economy and society towards a fair, green, and prosperous future [32].

The 'Fit for 55' package consists of 13 legislative proposals. Proposed changes to current EU regulations include: changing the European Union's Emissions Trading Scheme (EU ETS), reforming the LULUCF Regulation (Land Use, Land Use Change and Forestry), reviewing the Effort Sharing Regulation (ESR), amending the Renewable Energy Directive (RED), amending the Energy Efficiency Directive (EED), revising the Alternative Fuels Infrastructure Directive (AFID), amending the regulation on CO_2 emission performance standards for cars and vans, and revising the Energy Taxation Directive [33]. Novel legislative proposals include: a new EU Forest Strategy, a Carbon Border Adjustment Mechanism (CBAM), a social instrument for climate action, ReFuelEU Aviation (regarding sustainable aviation fuels), and FuelEU Maritime (regarding a green approach to maritime space) [34]. The main principles, rules, and objectives of 'Fit for 55' are presented in Table 1.

There are also EU-wide requirements in respect of the BIO component share in the conventional fuel blend, which also aims to significantly reduce CO_2 emissions. EU aims to boost the usage of renewable energy sources (RES) in the energy mix through its policy initiatives. Reports on ILUC (Indirect Land Use Change Impacts), ordered by the EC, raise doubts about the environmental sustainability of biofuels produced from grain, root/tuber, and oil crops [35]. As such, the usefulness of using food sources for biofuel production is being progressively scrutinized in discussions at the EU level. Thus, advanced (second- and third-generation) biofuels need to be used instead [36]. The reports list types of feedstocks used for biofuel production that are multiple-counted for the purposes of calculating biofuel energy content. Algae are first on that list. Thus, there is a real need to seek different sources of biomass for biofuels, ones which would be both commercially and environmentally viable.

Table 1. Overview of the EC's 'Fit for 55' package.

Pricing	Targets	Rules
New carbon border adjustment mechanism (CBAM) Updated Energy Taxation Directive Stronger Emissions Trading System including aviation, extending emissions trading to maritime, road transport, and buildings	Updated Energy Efficiency Directive Updated Renewable Energy Directive Updated Land Use, Land Use Change and Forestry Regulation Updated Effort Sharing Regulation	New infrastructure for alternative fuels Stricter CO_2 performance for cars and vans FuelEU: cleaner maritime fuels ReFuelEU: more sustainable aviation fuels
Support measures		
Combating climate change through the use of funds and regulations to foster innovation, enhance utility, and alleviate the effects on vulnerable communities through the establishment of the Social Climate Fund and improved Modernisation and Innovation Fund.		

4. Microalgae—Potential Use to Reduce CO_2 Emissions

Microalgae are single-celled microorganisms which turn solar radiation energy to chemical energy using photosynthesis [37]. Their biomass can contain numerous bioactive substances with high potential for both commercial and industrial use. Microalgae can produce a variety of cellular metabolites such as high quality proteins, lipids, carbohydrates, dyes, and vitamins for food/feed, cosmetics and alternative energy industries [38]. Microalgae employ a mechanism known as the carbon-concentrating mechanism (CCM) for CO_2 assimilation, using a specialized organelle (the pyrenoid) to raise CO_2 levels around thylakoid membranes [39]. The increased CO_2 levels around thylakoid membranes increase the efficiency of carboxylation/oxygenation of ribulose 1,5-bisphosphate (Rubisco), a photosynthesizing enzyme that plays a major role in carbon assimilation/sequestration. Rubisco has a low CO_2 binding affinity, having evolved in CO_2-rich and O_2-poor environments. As such, the pyrenoid acts to maintain optimal conditions for increased CO_2 binding capacity [40]. So far, various cellular components involved in transporting and storing inorganic carbon have been identified. However, the energy supply pathways for microalgae to accumulate CO_2 against the thermodynamic gradient remain unknown. Research has shown that in *Chlamydomonas reinhardtii*, the interaction between cyclic electron flow and O_2 photoreduction is crucial for the CO_2 concentration mechanism to function [41]. The process is dependent on the PGRL1 protein and flavodiron. The authors suggest that luminal protons are used downstream of thylakoid bestrophin-like transporters, possibly for the conversion of bicarbonate to CO_2. In addition, electron flow from the chloroplast to the mitochondria was found to contribute to the energization of non-thylakoid inorganic carbon transporters, possibly by providing ATP [41]. Microalgae-harnessing systems are increasingly considered for applications in engineering and environmental protection, especially in terms of wastewater treatment, solid waste neutralization, flue gas (including CO_2) reduction, and biofuel production technologies (Figure 5) [42]. Technologies based on the microalgae cultivation are considered to be applicable in environmental protection and engineering systems, as well as for the production of other economically valuable products, including fertilizers, feed additives, dietary supplements and energy carriers. The advantage of these microorganisms and the very wide application potential result from the high efficiency of photochemical processes, the rate of biomass production, genetic diversity and resistance to harsh environmental conditions in relation to typical terrestrial plants [43,44].

Research has extensively described microalgae-based technologies for flue gas treatment, pollutant degradation, and biofuel production. The microalgal biomass has been shown to be some of the most potent and environmentally friendly alternative energy sources. It offers a renewable source of bio-oil, methane and biohydrogen, the use of which can help reduce atmospheric CO_2 emissions [45]. Research suggests that the yield of bio-oil from microalgal cultures can surpass 19 m^3 oil/ha·year. By comparison, the corresponding values for other sources are: 6.1 m^3/ha·year for palm oil, 4.3 m^3/ha·year for sugar cane, 2.4 m^3/ha·year for maize, and 0.5 m^3/ha·year for soy [46]. The main perk of microalgae is their high photosynthetic efficiency, as they are able to convert 4% to 10% of light energy to chemical energy. By comparison, higher plants photosynthesize at 0.5–2.2% efficiency. Research has shown that microalgal cultures can produce 36 tons dry matter/ha·year, whereas soy yields only 2.6 tons grain/hectare· year (growing conditions being the same). Some microalgae strains can double their mass in a matter of hours, producing yields equivalent to 100 tons dry matter per hectare [47].

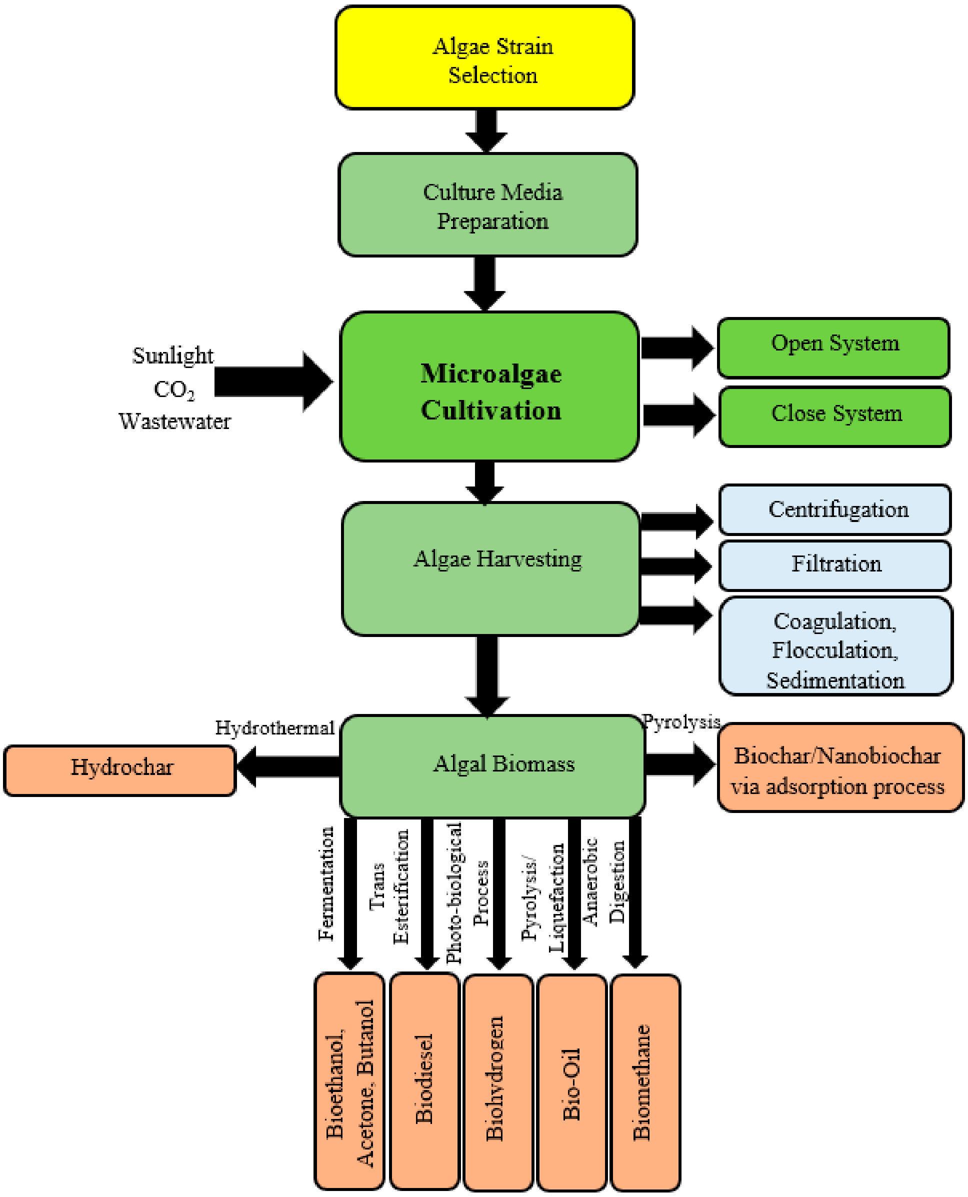


Figure 5. Technologies and avenues for application of microalgal biomass [42].

Another advantage of microalgal production systems is their potential to utilize waste, including sewage of various characteristics, leachates, semi-liquid waste, and gaseous emissions. Microalgae can take up nitrogen and phosphorus compounds. In mixotrophic cultures, they can also metabolize a portion of the organic load. Currently, microalgae-based waste treatment mechanisms are often integrated into systems intended to produce biofuels [48]. Such solutions are thought to be more feasible from the commercial and technological standpoint, while also being able to reduce CO_2 emissions from fossil fuels. Direct use of waste as a feedstock cuts the expenses of providing water and nutrients necessary for the algae to grow effectively [49]. Studies conducted to date demonstrate that elevated levels of CO_2 enhance microalgal growth and thus directly contribute to the elimination of other pollutants [50].

Eutrophicated and degraded water bodies used for phycoremediation may also serve as a reassuring source of microalgal biomass [51]. Obtaining microalgae from such reservoirs prompts to direct improvements in the quality of water. Controlled growth of microalgae in eutrophicated sea water directly lowers the biogenic compound levels in the water. It also reduces the probability of marine life loss and can be used as a form of revegetation to enhance the quality of water bodies [52]. Microalgae can be cultivated both in water acquisitioned from natural bodies (with high levels of biogenes), and in liquid waste and wastewater of varying compositions. This process not only leads to more efficient biomass productivity but can also bring positive environmental outcomes. Microalgal biomass can be grown without using pesticides, which significantly lowers the risk of secondary pollution [53].

The main barriers to rapid advancement of microalgae-based technologies lies in their associated investment and operation costs, technological complications related to the cultivation, thickening and separation of biomass, as well as the financial commitments required to convert biomass into value-added final products [54]. The investment and operating costs tied to microalgal cultivation are significantly higher (more than ten times higher in some cases) than those associated with obtaining lignocellulosic biomass [55]. As such, both commercial enterprises and research groups are working on increasing the cost-effectiveness of such systems as a priority. The absence of norms, standards, legislative measures, legal frameworks, and incentives (such as subsidies and tax credits) presents another obstacle to the broad use of microalgae production solutions for biofuel production [56].

Nevertheless, microalgae-based technologies are being systematically developed, and given the progress and optimization achieved in this regard, as well as the pressure caused by environmental challenges, global prospects are promising (Figure 6) [57]. Within the EU, there has also been a steady rise in the number of installations (both pilot- and full-scale) for the industrial production of microalgae (Figure 7) [58].

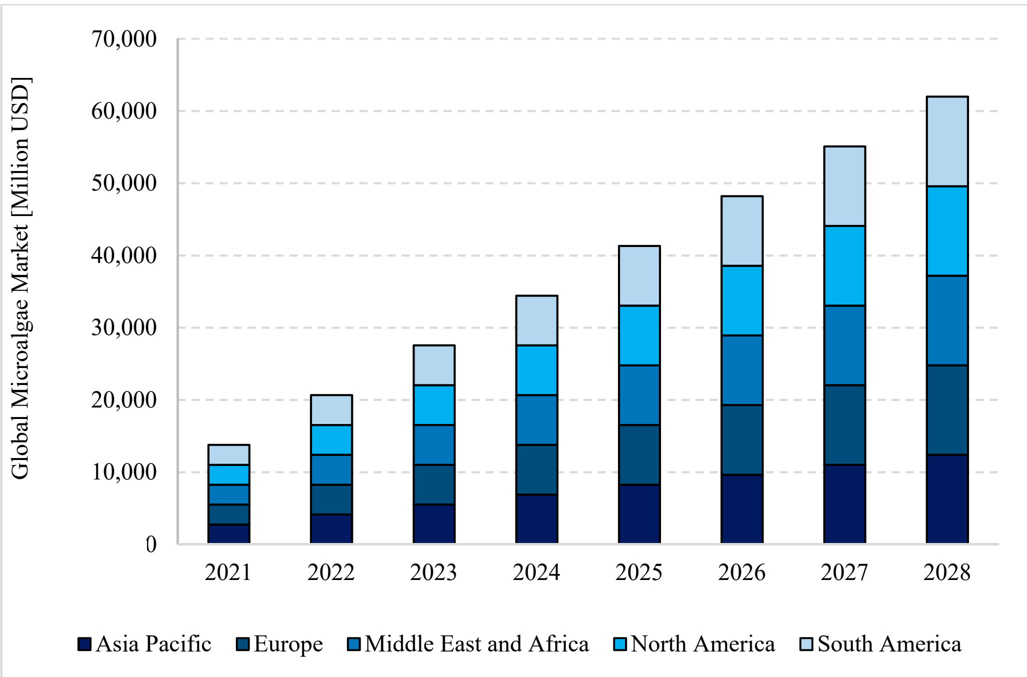


Figure 6. Global prospects for development of microalgae-based technologies [57].

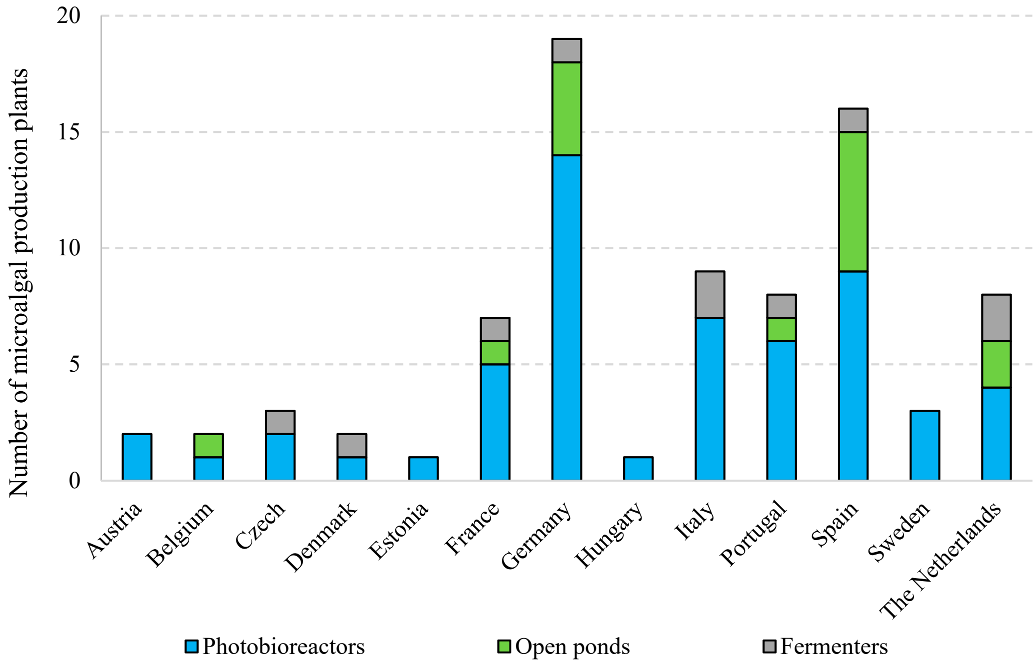


Figure 7. Number of microalgal production plants in the EU in 2021 [58].

5. Microalgal CO_2 Sequestration—The Current State of Knowledge

Results of experiments on microalgae-mediated CO_2 sequestration to date indicate that it can become an alternative and competitive technology to bolster current methods. It should be emphasized that the method harnesses biological systems, which require stable and reproducible conditions to thrive. With the large variety of anthropogenic CO_2 sources, each microalgae-based system will have to be tailored to the given industrial installation [59]. The literature data indicate that the composition of the released gas is determined by multiple factors, including the fuel from which the waste gas was produced, and how the system is used [60]. The CO_2 levels in the flue gas from combustion and other production processes (such as hydrocracking) fall within the wide range from 3 to 85% vol.

Microalgae-based biosequestration systems, known as photobioreactors (PBRs), have multiple limitations. Research has shown that CO_2 biosequestration efficiency can be severely impacted if the input gas contains high levels of sulfur oxides/nitrogen oxides/dust, or if it is heated to a high degree. In addition to CO_2, hundreds of other chemicals have been identified in the gases which can be fed into PBRs, and it is still unknown how these substances affect the photosynthetic process and its efficiency. It is reasonable to assume that many of them will have negative, inhibitory or toxic effects on the growing microalgae. At low concentrations, NO_x can be metabolized by microalgae and do not inhibit their metabolic activity. On the other hand, SO_x are toxic to microalgae [61]. A study by Stewart and Hessami [62] has demonstrated that a 4000 m^3 open system was able to remove 22,000 Mg CO_2/year. NO_x were taken up by the microalgal biomass as nutrients for growth. SO_x in the input gas should be less than 60 ppm [62].

So far, attempts have also been made to verify the possibility of using microalgae technologies in the processes of nitrogen oxide removal from exhaust gases. About 95% of them are dominated by NO, and the rest are N_2O, N_2O_3, NO_2, NO_3. The possibility of NO fixation by microalgae biomass is hindered by its low solubility in water, which is only 0.032 g/dm^3 at a pressure of 1 atm and a temperature of 25 °C [63]. Dissolution is prerequisite for using nitrogen oxides in the process of intensive growth of microalgae biomass. Nitrogen is used to build nucleic acids and proteins. Microalgae reduction of nitrogen oxides is a prospective method, but the research has never gone beyond the laboratory scale. It has been proven that NO at a concentration of about 300 ppm can be biologically converted to NO_2. Chiu et al. [64] proved that the average NO removal efficiency was 70% for *Chlorella* LEB-106, with a pollutant concentration of 100 ppm NO and 60 ppm SO_2. SO_2 dissolves very well in water at a rate of 22.971 g/100 gH_2O at 0 °C to 5.881 g/100 gH_2O at 40 °C. It was found that introducing gases with SO_2 concentration above 60 ppm into the culture should be avoided [64]. It has also been proven that the use of culture with a biomass concentration of 0.5 g/dm^3 reduces the sulfur toxicity to *Chlorella* MTF-7 cells, which were tolerant to SO_2 concentration of up to 90 ppm [64]. It is also believed that microalgae resistant to low pH conditions tolerate higher concentrations of this gas in the environment. Though there has been a noted decrease in the SO_x levels in flue gases in recent years (thanks to the use of effective desulfurization technologies), they are still high enough to reduce pH and carbonate levels in the growth medium. The toxic effects of these compounds are exacerbated under acid conditions [65]. High concentrations of SO_2 and CO_2 can lower pH and cause highly toxic substances to form in the medium. To alleviate this problem, systems are amended with alkalizing substances, including NaOH [66]. High concentrations of SO_2 can also damage photosynthetically-active pigments and proteins.

The performance of microalgae-mediated CO_2 sequestration is also strongly linked to the temperature of the gas. Highly heated gas can cause breakdown of chlorophyll and inhibit CO_2 bindings, as demonstrated for *Chlorella sorokiniana* [67]. Conversely, *Chlorella* MTF-7 has been shown to perform the best when exposed to gas at 30 °C. Increasing the temperature in the PBR to 40 °C led to significantly reduced microalgal biomass [64]. These optimal temperatures necessitate the use of cooling systems, as flue gas temperature can be as high as 450 °C.

The exact effect of increased CO_2 availability on microalgal biomass growth rates differs from species to species [68]. *Chlorella kessleri* has been shown to grow the fastest at 6% CO_2 in the PBR. Increasing CO_2 levels to 12% led to its lower population growth rates. On the other hand, the increase had no effect on *Scenedesmus obliquus* cultures, which are more tolerant [69]. The high solubility of CO_2 in aqueous solutions may lead to acidification of the medium and inhibition of the biochemical processes. *Chlorella* sp. KR-1 populations have been shown to grow well at CO_2 concentrations in the flue gas ranging between 10 and 70% vol. [70]. Similarly, Chiu et al. [71] demonstrated a direct link between CO_2 levels in the flue gas and biosequestration efficiency when using *Chlorella* sp. In their study, the CO_2 removal ranged between 16% and 58% across the variants [71]. Cheng et al. [72] tested the capacity of *Chlorella vulgaris* cultures to capture CO_2 from the air. The CO_2 capture efficiency was linked to CO_2 levels in the membrane-treated air. Integrating a membrane module with a PBR resulted in higher CO_2 removal compared with a conventional system–260 vs. 80 mg/dm^3·h, respectively [72]. A comparison of CO_2 sequestration rates across the experiments conducted to date is presented in Table 2.

Table 2. Literature data on the efficiency of microalgae-mediated CO_2 sequestration.

Species	Scale	photobioreactor Type	Growth Medium	Dry Matter Levels	Gas Type	CO_2 (%)	CO_2 Removal (%)	Ref.
Chlorella sp.	Laboratory	PBR	Modified f/2 medium in artificial sea water	8×10^5 cells mL^{-1} (low-density) or 8×10^6 cells mL^{-1} (high-density)	Air supplemented with CO_2	2–15	16–58	[71]
Chlorella sorokiniana	Laboratory	Air-lift PBR	Modified TAP (-acetate) medium	-	Flue gas	15.6	4.1	[67]
Chlorella sp. MTF-7	Laboratory	PBR	Modified f/2 medium in artificial sea water	0.1 g/L	Flue gas	25	60	[71]

Table 2. *Cont.*

Species	Scale	photobioreactor Type	Growth Medium	Dry Matter Levels	Gas Type	CO_2 (%)	CO_2 Removal (%)	Ref.
Chlorella kessleri	Laboratory	PBR	Bristol medium	0.15 g/L (dry biomass basis)	Air supplemented with CO_2 from a cylinder	6	-	[69]
Scenedesmus obliquus						12	-	
Chlorella sp. KR-1	Laboratory	Conical flasks	Modified M4N medium	0.1 g/L	Air supplemented with CO_2	10–70	-	[70]
Chlorella vulgaris	Laboratory	Membrane-PBR	Mineral medium	2×10^7 cells mL^{-1}	Air supplemented with CO_2	1	70	[72]
Chlorella vulgaris	Laboratory and large-scale	IMC-CO_2PBR	Synthetic medium	100 g DM/L	Flue gas	25	45	[73]
Scenedesmus obliquus WUST4	Pilot scale	Air-lift PBR	Modified soil extract medium (SE medium)	OD685 = 2.0 (OD685 is the optical density at 685 nm, which is used to indicate the algal biomass density based on the turbidimetry)	Flue gas	18	64	[74]
Dunaliella sp.	Pilot scale	Air-lift PBR	-	-	Flue gas	-	82.3 ± 12.5 (sunny days) 50.1 ± 6.5 (cloudy days)	[75]
Mixed biodiverse microalgal (*Desmodesmus* spp. were identified as dominant microalgae)	Pilot scale	PBR	Bold Basal Medium and f/2 medium	0.1–0.4 g/L	Flue gas	11	-	[76]
Chlorella sp.	Pilot scale	PBR	Macronutrients (technical grade)–urea	-	Flue gas	6–8	10–50	[77]

Apart from the aforementioned primary determinants of effective CO_2 biosequestration in microalgae-based systems, there are other major factors: PBR illumination, gas flow, and biomass concentration in the medium, as well as the methods used for stirring, for ensuring optimal gas retention in the biosequestration zone, and for maintaining interphase contact. The type of culture system, and the mechanism used to supply CO_2-rich gas, are factors cited as the most important [78].

6. Photobioreactors Used for CO_2 Biosequestration

A key factor, which in many cases determines the cost-effectiveness of microalgae-based systems, is the choice of culture method [79,80]. Algal biomass can be cultivated using a variety of methods, ranging from strictly monitored/controlled methods in technologically advanced designs to the less predictable methods based on open systems. The biomass can also be sourced from natural water bodies. The most commonly used systems for the production and extraction of microalgal biomass are presented in Figure 8.

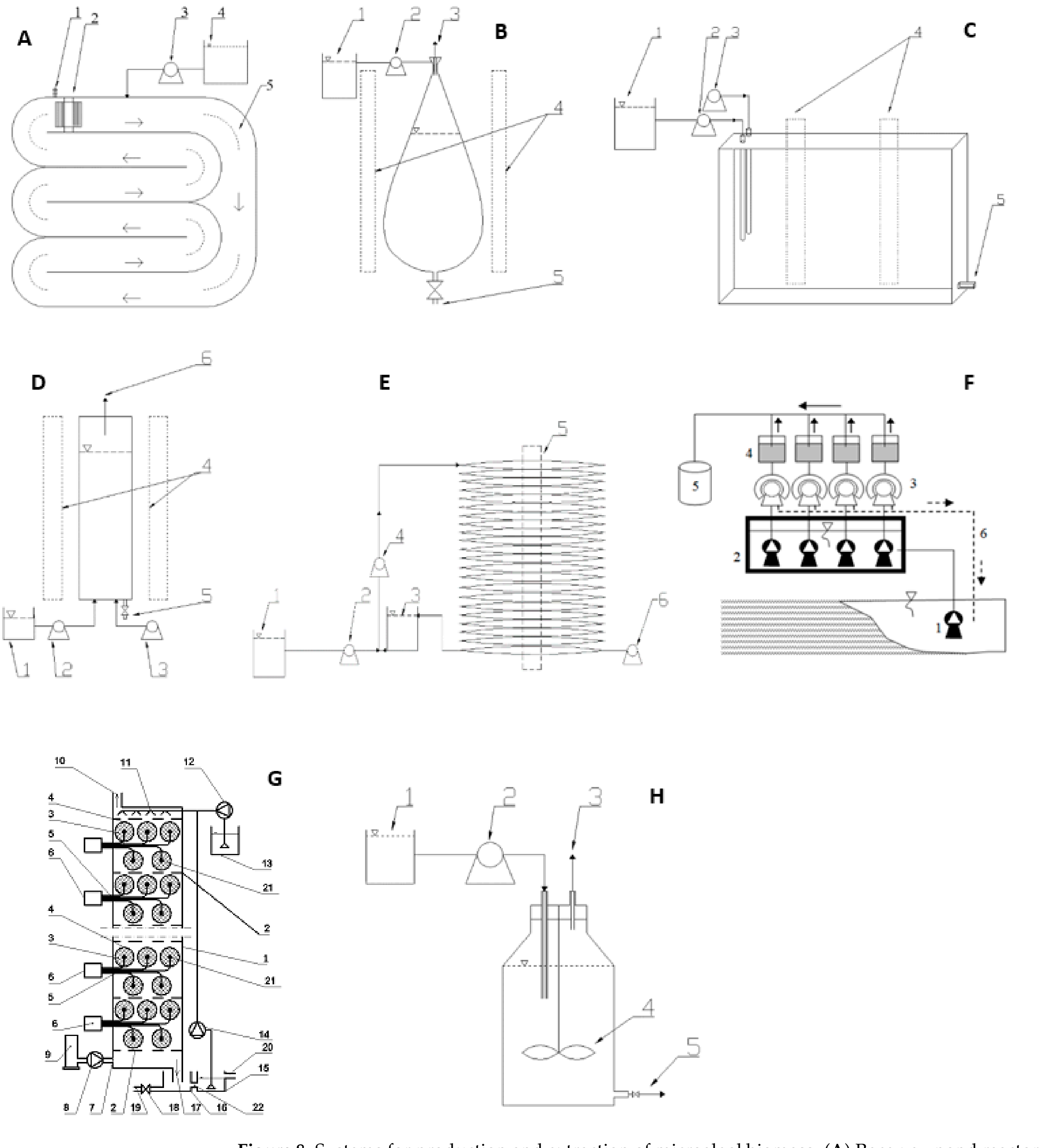


Figure 8. Systems for production and extraction of microalgal biomass. (**A**) Raceway pond reactor (1—biomass extraction, 2—agitator blade, 3—nutrient dosing pump, 4—medium tank, 5—baffle). (**B**) Sack-type photobioreactor (1—medium tank, 2—nutrient dosing pump, 3—gas vent, 4—light source, 5—air supply and biomass extraction). (**C**) Flat plate photobioreactor (1—medium tank, 2—nutrient dosing pump, 3—air pump, 4—light source, 5—biomass extraction). (**D**) Tubular photobioreactor (1—medium tank, 2—nutrient dosing pump, 3—air pump, 4—light source, 5—biomass extraction, 6—gas outflow). (**E**) Biocoil-type photobioreactor (1—medium tank, 2—nutrient dosing pump, 3—biomass extraction, 4—recirculating pump, 5—light source, 6—air pump). (**F**) Installation for sourcing microalgal biomass from natural water bodies (1—intake pump, 2—settlement tank, 3

—series of drum filters, 4—separated algal biomass, 5—tank for biomass, 6—discharge). (**G**) Immobilized microalgae-based photobioreactor for CO_2 capture (1—photobioreactor housing, 2—support grid, 3—immobilized microalgal biomass, 4—capsule membrane, 5—fiber-optic cable, 6—light source, 7—CO_2 in, 8—gas pump, 9—CO_2 tank, 10—gas outlet, 11—nozzle, 12—growth medium dosing pump, 13—growth medium tank, 14—rinse pump, 15—settlement tank, 16—separation tank for excess algal biomass (including blue-green algae), 17—outlet, 18—valve, 19—discharge line, 20—liquid outlet, 21—in-capsule end of the optic-fiber cable, 22—line). (**H**) Diagram of a heterotrophic microalgal culture reactor (1—medium tank, 2—nutrient dosing pump, 3—gas outflow, 4—mechanical stirrer, 5—biomass extraction).

In systems that can be scaled up, using open cultures is often a way to reduce investment and operating costs [81] (Figure 8A). These usually consist of landlocked reservoirs with an area of 250 ha and depth of 0.5 m at most, either as circular ponds or raceway ponds stirred by agitator blades. These systems are handicapped by water losses through evaporation during operation, relatively low biomass growth, limited compatibility with certain algae species, and high vulnerability to infections, diseases, and parasites. These types of systems work well in areas with high sun exposure and unlimited access to water, which mostly relegates them to coastal areas. This technique is mainly used to grow *Spirulina* sp., *Chlorella* sp., and *Scenedesmus* sp. algae [82].

Sack systems of "large bags" are an example of a simple closed PBR design (Figure 8B), operating on a periodic or semi-continuous basis [83]. The main problem of this system is that the culturing process has to be conducted indoors and requires extensive additional lighting. Reactors of this type also fail to provide proper mixing, which limits biomass production. A variety of designs for flat plate reactors, as well as PBRs with vertical panels with separators, have been presented for growing different strains of algae [84] (Figure 8C).

Tubular reactors are usually built from glass or polycarbonate, with growth medium and gas being fed into the system using pumps or air lift systems [85] (Figure 8D). Such units can be horizontal, vertical, or inclined at an angle or conical. The biocoil reactor is a sub-type of the tubular photobioreactor (Figure 8E). It consists of a transparent hose wrapped around a core cylinder [86]. Microalgal biomass can also be obtained via phytoremediation (Figure 8F). This technology is designed to extract and separate microalgae from eutrophic/degraded natural water bodies, for their remediation and improvement of their trophic state. The efficiency of CO_2 biosequestration is constrained by the comparatively low microalgal biomass levels in the cultivation medium. Therefore, there is an undeniable need to seek different solutions—ones which would be comparable in terms of performance and affordability [87]. One such alternative is to use PBRs that harness immobilized microalgae to CO_2 fixation from flue and exhaust gas (IMC-CO_2PBR) (Figure 8G). This microalgae immobilization technology produces biomass yields close to 100 g DM/dm^3, thus offering far better CO_2 capture capacity than the conventional technologies [73]. It is also possible to grow and cultivate algal biomass in mixotrophic or heterotrophic systems, in which suitable carbon compounds are supplied to the bioreactors as nutrients for microalgae (Figure 8H). However, since the biomass is often grown without light or photosynthesis, these systems have limited applicability for CO_2 biosequestration. A comparison of microalgal culture systems is presented in Table 3.

Table 3. Comparison of technologies for microalgae-mediated CO_2 biosequestration.

Production System	Prospects	Limitation	Ref.
Open systems	Good for mass cultivation. Relatively economical after cultivation. Easier to construct, operate and clean up.	Requirement of large areas of land. Easily contaminated. Poor light utilization. Diffusion of CO_2 to the atmosphere. Evaporative losses. Limited to few strains of algae, cultures.	[88–90]

Table 3. *Cont.*

Production System	Prospects	Limitation	Ref.
Flat panel photobioreactor	Low accumulation of dissolved oxygen and high concentration of sunlight per cm^2. Modular design makes it easy to scale up production.	Algal biofilm formation. Strain-specific hydrodynamic stress issues. Temperature control issues.	[83,91,92]
Tubular photobioreactor	Good biomass productivities. Relatively inexpensive Suitable for outdoor.	Adverse pH and CO_2 gradients. High levels of dissolved oxygen. Fouling. Photoinhibition is very common (outdoor).	[93–95]
Tic bag photobioreactor	Good sterility. Low cost.	Disposal of used plastic bags may present a significant challenge at large scale operation.	[96–98]

7. Methods of Feeding CO_2 to Microalgae Photobioreactors

To optimize production of microalgal biomass and thus improve the resultant CO_2 capture capacity, the gas input to the growing microorganisms has to match their demand for gas. The well-known and widely used CO_2 delivery methods, based on diffusion and aeration, do not provide adequate performance [99]. Therefore, efficient and cost-effective methods for medium carbonization need to be developed to improve the performance of microalgae-based CO_2 biosequestration systems.

One of such methods is to supply compressed air, pure CO_2, or exhaust/flue gas. The gaseous CO_2 carrier is fed into the medium via a diffuser system at the bottom of the PBR. This method is, however, hampered by low performance, mainly due to the short retention time of gas bubbles in the culture medium, which limits the availability and transfer of CO_2 to the microalgae biomass. It is characterized by significant losses of CO_2 and high operation costs, due to the need to compress and supply the gas. It is estimated that up to 90% CO_2 fed into photobioreactors is not bioassimilated and is instead discharged from the system. When aeration is used to increase CO_2 biosequestration rates, the size of the gas bubbles in the medium can be progressively reduced to bolster performance [100]. It has been demonstrated that microbubbles and nanobubbles promote CO_2 dissolution and its subsequent metabolization by microalgae. This stems from the increased surface-to-volume ratio of gas bubbles and retention time in the microbial activity zone. This method has been adopted from aerobic wastewater treatment technologies using activated sludge, designed with extensive oxidization of pollutants in mind. However, smaller bubble sizes produced by diffuser systems require higher energy expenditure, which drives up the cost of the process. In addition, this type of pressurized injection can generate huge shear forces, potentially damaging microalgae cell structures and thus inhibiting biological activity and CO_2 biosequestration efficiency [101]. Shear forces, which are destructive to microalgae, can be mitigated or eliminated by using intermediate tanks and carbonization columns to which the microalgal biomass is transported for mixing with CO_2. Sparging or stirring systems have been found to accelerate the process. When carbonization columns are used, the culture medium mixed with microalgae biomass is poured in from above via sprinklers to ensure the countercurrent flow of medium and gas [102].

Membrane diffusers can be used to maintain the gas–liquid interface during CO_2 supply and retention time in culture medium [103]. The membranes can be used with aeration or membrane contactors. The CO_2 is compressed during membrane separation to generate gas bubbles 1–2 mm in size. When traditional diffuser systems are used, the gas bubble size ranges from 5 to 8 mm. The small pore sizes on the membranes necessitate high gas pressures. Membrane systems also require large surface areas and fine control of CO_2 pressure. In addition, they are sensitive to biological fouling during biofilm formation on the surface, which necessitates cleaning and periodic shutdowns [104].

Carbonization of the growth medium can be effected by using bicarbonate solutions. The inorganic carbon in the medium consists of CO_2, HCO^{3-}, and $CO_3{}^{2-}$. Specific concentrations of these carbon species are a function of pH, alkalinity, salinity, and temperature. All photoautotrophic species of microalgae can directly utilize CO_2. Many species are also able to take up and biochemically convert HCO^{3-} [105]. Microalgae-mediated CO_2 sequestration systems thus depend on maintaining pH in the medium between 7 and 8, so that the inorganic carbon dissolved in the medium is kept in the form of CO_2 and HCO^{3-}. With the confirmed capacity of microalgae to take up HCO^{3-}, carbonization of the culture medium can be boosted. The literature confirms that sodium carbonate can be used to grow microalgae [106]. High concentrations of bicarbonate salts have been shown to increase medium alkalinity, which inhibits microalgal population growth in the long-term and, in extreme cases, can be toxic to the culture, resulting in poorer CO_2 biosequestration efficiency. This can be counteracted by using species resistant to and tolerant of extreme conditions, by slowly adapting the microalgae to increased medium alkalinity/salinity, and by supplementing the culture with dual streams of CO_2 and HCO^{3-} gas. Bicarbonate solutions increase the alkalinity in the culture, which can enhance CO_2 dissociation in the medium. Although studies on bicarbonate salts have been promising and have, in many cases, shown improved microalgal biomass growth, this method is still commercially inferior to gaseous CO_2 [107]. System performance as a function of the tested microalgae species and the mechanism of gas supply into the PBR is presented in Table 4.

Table 4. Biomass production and CO_2 sequestration rates as a function of pre-treated gas input method.

Species	Supply Method	CO_2 Supply (%, *v*/*v*)	Scale	Biomass Produced (g/Ld)	CO_2 Removal Efficiency (%)	CO_2 Fixation Rate (g/Ld)	Ref.
Botryococcus braunii	Sparging	0.03	1 L glass bottle	0.04	-	0.08	[108]
Botryococcus braunii		10	1 L glass bottle	0.02	6.78 ± 3.58	0.03	[108]
Botryococcus braunii		20	1 L glass bottle	0.03	3.73 ± 0.74	0.05	[108]
Chlorella pyrenoidosa		1	2 L flask	0.24	-	0.49	[109]
Chlorella pyrenoidosa		10	1.8 L bubble column	0.14	95.1	0.25	[110]
Chlorella sorokiniana		1	2 L flask	0.29	-	0.58	[109]
Chlorella vulgaris		0.03	1.5 L membrane bioreactor	0.05	-	0.09	[111]
Chlorella vulgaris		10	1.8 L bubble column	0.07	95.3	0.13	[110]
Scenedesmus dimorphus		10	1.8 L bubble column	0.12	94.6	0.22	[110]
Scenedesmus obliquus		10	1.8 L bubble column	0.15	94.7	0.27	[110]
Scenedesmus sp.		20	1 L glass bottle	0.13	3.82 ± 1.71	0.23	[108]

8. Microalgae as a Way of Capture and Utilization of CO_2 (CCU)

Utilization of captured CO_2 removes the need for its storage and containment. CO_2 capture and utilization/re-use is defined in terms of conversion into value-added, lower-/zero-emission products, including fuels, chemicals, carbon fibers, biomass, and building materials. The CCU (carbon capture and utilization) should prove to be a useful tool in achieving zero/negative net emissions [112].

Microalgae-mediated CCU is a biotechnological process. In its first stage, CO_2 is converted to biomass via photosynthesis [113]. The resultant biomass can be used to replace non-renewable fossil resources in the production of chemicals, fuels, bioplastics, diet supplements, cosmetics, pharmaceuticals, feedstuffs, and fertilizers.

Technologies for converting microalgae biomass to energy can be divided into two main groups: thermochemical and biochemical [114]. The production of biofuels from microalgae includes dark fermentation with methane [115] or hydrogen recovery [116], alcoholic fermentation to bioethanol [117], production of hydrogen from direct biophotolysis [118,119], production of biodiesel from storage lipids [120,121], pyrolysis gas [122] or syngas recovery [123] in thermal processes, and energy recovery from direct combustion of microalgae biomass [124]. In the energy transformation technologies of microalgae, apart from energy carriers, waste is generated, which is often used as fertilizer in agronomy [125].

Microalgae can be used as a potential tool for long-term CO_2 capture and utilization (Table 5)–for example, in the production of cement or bioplastics [126]. Production and utilization of biocarbon is another avenue of microalgae application–fixing carbon into soil provides long-term storage of CO_2 and serves to promote sustainable agriculture. Microalgae can also potentially be used as biostimulants to improve crop production, thereby reducing the need for chemical fertilizers. Microalgal biomass can also be used to produce bioplastics through CO_2 biosequestration [127]. Bioplastics are environmentally-friendly materials, as they do not increase the CO_2 pool and are quicker to biodegrade. Microalgae can contain high levels of polysaccharides, proteins or lipids, and may thus serve as an alternative to other bioplastics and replace traditional plastics and biodegradable materials (such as polylactic acid and polyhydroxyalkanoates). Biodegradable bioplastics reduce the pollutant load on oceans and reduce landfill areas, currently overfilled with non-degradable plastics. Using microalgae for cement production can serve as another method of long-term CO_2 capture. The process involves the precipitation of $CaCO_3$ by certain photosynthetic microalgae or blue-green algae, as well as non-phototrophic bacteria [111].

Table 5. Comparison of long-term products made with microalgal biomass that can help achieve negative CO_2 emissions.

Species	Product	Characteristics	Ref.
Chlorella pyrenoidosa	Biocarbon	Highly microporous design and heteroatom-containing composition of the sustainable biocarbon will make it an attractive material for a lot of applications, including supercapacitors, CO_2 capture, and catalysts for oxygen reduction reaction.	[128]
Chlorella pyrenoidosa			[129]
Scenedesmus sp.			[130]
Graesiella sp. WBG-1			[131]
Chlorella sp., *Scenedesmus* sp., *Spirulina* sp., *Synechocystis* sp.	Biostimulants	Sustainable and economical substitute to synthetic liquid fertilizer for promotion of eco-agriculture.	[132]
Tetradesmus obliquus, *Chlorella protothecoides*, *Chlorella vulgaris*			[133]
Chlamydomonas reinhardtii, *Chlorella sorokiniana*			[134]
Scenedesmus sp. UTEX 1589	Bioplastics	They have great biodegradability, biocompatibility, and properties comparable to regular thermoplastics. Being derived from sustainable natural materials, these biopolymers establish to solve the environmental issues caused by petrochemical plastics. Thanks to the combination of their unique characteristics, PHAs have the ability to be used in a wide variety of applications. Their biodegradability and biocompatibility allow their use in medical utilization, e.g., in the manufacture of implants, wound dressings, or drug delivery carriers.	[135]
Nannochloropsis			[136]
Spirulina			[137]
Chlamydomonas reinhardtii 11-32A			[138]

Table 5. *Cont.*

Species	Product	Characteristics	Ref.
Chlorella kessleri	Cement	Biocement is a competitive material compared to conventional products. Its manufacturing is economically and environmentally justified as high temperatures are not required. Biocement is used to repair damaged structures and to strengthen eroding rock formations.	[139]
Chlorella vulgaris			[140]
Synechococcus elongatus and Spirulina platensis			[141]

9. Blue Carbon and Phycoremediation

Phycoremediation is the process of harnessing macroalgae, microalgae, and blue-green algae for the removal or bioconversion of toxic and resistant pollutants present in aquatic ecosystems and capturing atmospheric CO_2 as a way of improving the environment [142]. This method, based on natural ecosystems, has been shown to be commercially and environmentally viable thanks to its efficiency and the global abundance of sea/ocean waters. The term 'blue carbon' refers to the CO_2 removed from the atmosphere by oceanic ecosystems, in particular phytoplankton, algae, macroalgae, mangroves, seagrass meadows, and saltmarshes, through the growth of plants and accumulation/embedding of organic matter in soil and sediments. The contribution of natural ecosystems and phytoplankton to atmospheric CO_2 sequestration is presented in Table 6. Microalgae are the largest contributors to this type of CO_2 biosequestration, removing an estimated 12,000 $MgCO_2/km^2 \cdot year$ [143].

Table 6. Mechanism and contribution of microalgae to the blue carbon concept.

Blue Carbon Warriors	CO_2 Sequestration Intensity [$MgCO_2/km^2 \cdot year$]	Total Carbon Sequestration [TgC/year]
Mangroves	829	31.45
Salt marshes	799	11.12
Seagrasses	506	44.02
Cultured macroalgae	1500	0.68
Coral reefs	543	16.5
Wild macroalgae	150	173
Microalgae	11,280	Not available

In the oceans, carbon can be sequestered in the natural environment or through controlled cultures of microalgae/macroalgae. Developing blue carbon strategies, initiatives, and projects can bring many benefits, e.g., carbon capture and storage, improvement of the trophic state of oceans (removal of the excess nutrients that cause eutrophication), and improvement of sea ecosystem health (restoration of marine life) [144]. Controlled cultures of microalgae not only benefit the environment, but can also provide marketable products, such as alternative foodstuffs, diet supplements, low-emission animal feed, and other algae-derived products (including those that fix CO_2 in the long term) [145]. Notably, seas and oceans are the largest ecosystems that act as a "biological carbon pump", sequestering CO_2 in organic compounds or minerals (mainly through the primary production of phytoplankton). Through this process, each year approx. 10 gigatons of carbon are drawn from the atmosphere into the oceans worldwide [146]. Even minor fluctuations in the proliferation of sea microalgae can influence atmospheric CO_2 levels and global warming.

Dębowski et al. [147] have explored ways to improve the trophic state of oceans by removing phytoplankton biomass. Their experiments support the applicability of microalgal biomass from natural reservoirs as a potential substrate in biogas production systems. In addition, they have shown that the choice of growing season for biomass harvest and the related taxonomic structure have a direct impact on the anaerobic processes and their final products [147]. In the same vein, Zhong et al. [148] described ways of using algal biomass to produce biofuels, focusing on *Cyanoprokaryota* sourced from the eutrophicated Lake Taihu in China [148]. Extensive blue-green algal blooms, during which the growing phytoplankton biomass binds significant amounts of CO_2, are an increasingly common phenomenon in many natural water bodies around the world. Capturing and utilizing microalgal biomass from natural water bodies can help improve the trophic state of those bodies, while also improving air quality. Microalgal biomass growth in eutrophicated/degraded water bodies can be enormous, sometimes reaching hundreds of tons per day. The work of these authors, as well as that of other researchers, speaks to the growing interest in this organic substrate as a potential source of organic matter for producing biogas [149,150].

However, it is important to note that achieving stable CO_2 biosequestration in water bodies located in the temperate zone and cooler climates throughout the entire growing season is a problematic endeavor. The main barriers are those related to changes in the weather, which directly impact the amount of harvestable biomass, the taxonomic structure of the algae, and the properties/parameters of the resultant organic substrate [151]. Extraction is both technologically and commercially impractical during winter seasons due to the reduced growth, low concentrations of algal biomass in natural water bodies, and frequent appearance of ice cover. Capturing and utilizing microalgal biomass from eutrophicated surface waters may also pose operational and technological hurdles (variable quality and yields of biomass, costs of harvesting) [152].

10. Future and Prospects

The EU has adopted a highly ambitious strategy for bioeconomy development. Within this framework, microalgae and their prospective applications in various fields represent a crucial biological resource. In particular, microalgae are currently being promoted for their wide-ranging applications in environmental technologies, bioenergy production, and as a source of valuable nutrients for humans and animals [153]. The microalgae sector will gain a growing position in the EU's blue bioeconomy and has great growth potential, especially in areas near the coast. The EU's blue algae industry has yearly revenue of EUR 1.5 billion and indirect activities (research, etc.) contribute an additional EUR 240 million [154].

In the EU, algal biomass (mainly macroalgae) is largely harvested from natural water bodies. There has been a noted reduction of populations and species, that are commercially exploited in the EU. This is mainly associated with global warming, overexploitation and harvesting of biomass, environmental degradation of aquatic ecosystems, and displacement of endemic species that leads to non-native species rapidly spreading [151]. Therefore, it is necessary to build and operate dedicated facilities for algal biomass production. Microalgae have a competitive advantage, owing to their capacity for efficient photosynthesis, high rate of biomass growth, resistance to harsh environmental conditions, and ability to metabolize many pollutants [155]. Microalgae aquaculture has been shown to achieve the environmental benefits of phycoremediation, while also meeting the increasing demand for algal biomass and reducing pressure on wild populations [156].

It is thus clear that there is a need for solutions that improve the technological, environmental and commercial viability of technologies for producing and utilizing microalgal biomass. However, more research is needed to assess the full environmental impacts of such systems; water, energy and land use; risk of releasing invasive species into the environment; and perception/awareness among local communities. In the EU, unsuitable climate conditions are an additional barrier to large-scale and effective production of microalgal biomass [157]. This directly induces the obligation of preparing such facilities with solutions that assure the appropriate thermal and light settings—crucial factors in microalgae growth. However, these additions make the cost associated with investment and operating increase significantly [158].

A proven way to improve economic efficiency is the use of waste, including wastewater and exhaust gases, as basic components of culture medium [159]. Therefore, a promising solution is to integrate microalgae biomass production systems with municipal management facilities, wastewater treatment plants or agricultural or utilization biogas plants. These types of installations can ensure the right amount and quality of nutrients, including biogenic compounds, and provide a source of carbon dioxide and allow the use of waste heat [160].

Important aspects supporting and stimulating the development of CO_2 capture systems by microalgae are legislative actions leading to GHG emission reduction and supporting the development of renewable energy sources (RES). An example is the requirements for the share of BIO components in liquid fuels, which require a wider use of biofuel technologies [161]. The EU policy aims to increase the share of RES in the energy mix and to reduce CO_2 emissions, which is a challenge for all member states. This balanced approach is not changed drastically by the current situation related to limited access and rising prices of conventional energy carriers. The Indirect Land Use Change Impacts (ILUC) reports review the approach taken so far and challenge the ecological viability of crop-based bioenergy production. Therefore, it is necessary to search for and implement solutions based on the use of advanced biofuels produced from non-food raw materials. Microalgae are mentioned at the top of the list of potential raw materials for the production of biofuels [162].

Biosequestration of CO_2 by microalgae is a biological process, the course and effectiveness of which are influenced by many environmental, technological, and operational factors. Climatic conditions, the intensity and duration of insolation, temperature, as well as the availability of a natural and unlimited water source are of great importance, especially for the economics of the process [163]. The biotechnological factors include the use of selected strains of microalgae and the implementation of molecular engineering techniques to increase the efficiency of photosynthesis, improve the tolerance of microalgae to difficult and changing environmental conditions, and increase the rate of biomass growth and removal of pollutants [164]. The technological and operational parameters concern the lighting method, the type and method of dosing culture medium, the intensity of gas feeding, the degree of their preliminary purification, the type of photobioreactor, and the method of microalgae biomass separation [165]. The most important issue, however, is the optimization of the technological system for CO_2 biosequestration by microalgae towards achieving the technological and economic efficiency of the process.

11. Conclusions

The use of microalgae biomass for industrial purposes, including CO_2 capture, is not a new idea, but has been systematically developed for many years. Due to their features and characteristics, these microorganisms are seen as a prospective alternative to the chemical and physical CO_2 capture methods. However, the widespread and dynamic development of this type of technology is still very limited. The most important factor hindering the widespread implementation of these solutions is still too low technological readiness level and insufficient large-scale verification tests. The observed dynamics of investments are low and do not correspond to the rank assigned to microalgae technologies. It should be clearly stated that the current efficiency of microalgae technology is too low to compete with other CO_2 capture techniques or the production of conventional energy carriers. An important factor is also the volatility and instability of energy prices and CO_2 emission allowances.

The main barriers to the development of microalgae technology are the very complex and multi-variable nature of microalgae cultivation, as well as the lack of sufficient data from installations operated in commercial conditions, which in many cases prevents a reliable assessment of the life cycle. There is also a lack of sufficient legal and subsidy support for such innovative installations. The increase in efficiency can be seen in the implementation of optimization techniques, the use of genetic engineering and the intensification of production with advanced monitoring and process control techniques. However, considering the long-term environmental, energy, and climate policy of the EU, technologies based on the use of microalgae should still be considered as very prospective. Their development is supported both by inclusion in the applicable strategies of the future, as well as financial support for research projects aimed at optimization and improvement of these types of CO_2 capture techniques.

It must be noted that the scale and dynamics of microalgae technologies development in the future depends on many factors that are difficult to predict. These include aspects related to climate policy, the evolution dynamics of competitive and alternative technologies and, above all, the economic aspects of such solutions.

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Abbreviations

CO_2	carbon dioxide,
GHG	greenhouse gas,
EU	European Union,
EC	European Commission,
EU ETS	European Union's Emissions Trading Scheme,
LULUCF	Land Use, Land Use Change and Forestry,
ESR	Effort Sharing Regulation,
RED	Renewable Energy Directive,
EED	Energy Efficiency Directive,
AFID	Alternative Fuels Infrastructure Directive,
CBAM	Carbon Border Adjustment Mechanism,
RES	renewable energy sources,
ILUC	Indirect Land Use Change Impacts,
CCM	carbon-concentrating mechanism,
PBRs	photobioreactors,
TAP medium	Tris-Acetate-Phosphate medium,
SE medium	soil extract medium,
IMC-CO_2PBR	Immobilized microalgae-based photobioreactor for CO_2 capture,
PHAs	Polyhydroxyalkanoates

References

1. Iqbal, N.; Abbasi, K.R.; Shinwari, R.; Guangcai, W.; Ahmad, M.; Tang, K. Does Exports Diversification and Environmental Innovation Achieve Carbon Neutrality Target of OECD Economies? *J. Environ. Manag.* **2021**, *291*, 112648. [CrossRef] [PubMed]
2. Nunes, L.J.R.; Dias, M.F. Perception of Climate Change Effects over Time and the Contribution of Different Areas of Knowledge to Its Understanding and Mitigation. *Climate* **2022**, *10*, 7. [CrossRef]
3. Bouzarovski, S.; Thomson, H.; Cornelis, M. Confronting Energy Poverty in Europe: A Research and Policy Agenda. *Energies* **2021**, *14*, 858. [CrossRef]
4. Olabi, A.G.; Abdelkareem, M.A. Renewable Energy and Climate Change. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112111. [CrossRef]
5. Rehman, A.; Ma, H.; Ozturk, I.; Ulucak, R. Sustainable Development and Pollution: The Effects of CO_2 Emission on Population Growth, Food Production, Economic Development, and Energy Consumption in Pakistan. *Environ. Sci. Pollut. Res.* **2022**, *29*, 17319–17330. [CrossRef]
6. Borowski, P.F. Management of Energy Enterprises in Zero-Emission Conditions: Bamboo as an Innovative Biomass for the Production of Green Energy by Power Plants. *Energies* **2022**, *15*, 1928. [CrossRef]
7. Shakoor, A.; Shakoor, S.; Rehman, A.; Ashraf, F.; Abdullah, M.; Shahzad, S.M.; Farooq, T.H.; Ashraf, M.; Manzoor, M.A.; Altaf, M.M.; et al. Effect of Animal Manure, Crop Type, Climate Zone, and Soil Attributes on Greenhouse Gas Emissions from Agricultural Soils—A Global Meta-Analysis. *J. Clean. Prod.* **2021**, *278*, 124019. [CrossRef]
8. Stokreef, S.; Sadri, F.; Stokreef, A.; Ghahreman, A. Mineral Carbonation of Ultramafic Tailings: A Review of Reaction Mechanisms and Kinetics, Industry Case Studies, and Modelling. *Clean. Eng. Technol.* **2022**, *8*, 100491. [CrossRef]

9. Lee, B.J.; Il Lee, J.; Yun, S.Y.; Hwang, B.G.; Lim, C.S.; Park, Y.K. Methodology to Calculate the CO_2 Emission Reduction at the Coal-Fired Power Plant: CO_2 Capture and Utilization Applying Technology of Mineral Carbonation. *Sustainability* **2020**, *12*, 7402. [CrossRef]
10. Middleton, R.S.; Ogland-Hand, J.D.; Chen, B.; Bielicki, J.M.; Ellett, K.M.; Harp, D.R.; Kammer, R.M. Identifying Geologic Characteristics and Operational Decisions to Meet Global Carbon Sequestration Goals. *Energy Environ. Sci.* **2020**, *13*, 5000–5016. [CrossRef]
11. Chao, C.; Deng, Y.; Dewil, R.; Baeyens, J.; Fan, X. Post-Combustion Carbon Capture. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110490. [CrossRef]
12. Vale, M.A.; Ferreira, A.; Pires, J.C.M.; Gonçalves, G.A.L. CO_2 Capture Using Microalgae. *Adv. Carbon Capture Methods Technol. Appl.* **2020**, 381–405. [CrossRef]
13. Liu, T.; Chen, Z.; Xiao, Y.; Yuan, M.; Zhou, C.; Liu, G.; Fang, J.; Yang, B. Biochemical and Morphological Changes Triggered by Nitrogen Stress in the Oleaginous Microalga *Chlorella vulgaris*. *Microorganisms* **2022**, *10*, 566. [CrossRef] [PubMed]
14. de Kleijne, K.; Hanssen, S.V.; van Dinteren, L.; Huijbregts, M.A.J.; van Zelm, R.; de Coninck, H. Limits to Paris Compatibility of CO_2 Capture and Utilization. *One Earth* **2022**, *5*, 168–185. [CrossRef]
15. Schönfeld, K.C.; von Ferreira, A. Urban Planning and European Innovation Policy: Achieving Sustainability, Social Inclusion, and Economic Growth? *Sustainability* **2021**, *13*, 1137. [CrossRef]
16. European Commission. European Climate Law. Available online: https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en (accessed on 29 December 2022).
17. Wang, Q.; Jiang, X.T.; Yang, X.; Ge, S. Comparative Analysis of Drivers of Energy Consumption in China, the USA and India—A Perspective from Stratified Heterogeneity. *Sci. Total Environ.* **2020**, *698*, 134117. [CrossRef] [PubMed]
18. Aktar, M.A.; Alam, M.M.; Al-Amin, A.Q. Global Economic Crisis, Energy Use, CO_2 Emissions, and Policy Roadmap amid COVID-19. *Sustain. Prod. Consum.* **2021**, *26*, 770–781. [CrossRef]
19. Davis, S.J.; Liu, Z.; Deng, Z.; Zhu, B.; Ke, P.; Sun, T.; Guo, R.; Hong, C.; Zheng, B.; Wang, Y.; et al. Emissions Rebound from the COVID-19 Pandemic. *Nat. Clim. Chang.* **2022**, *12*, 412–414. [CrossRef]
20. Global Carbon Project. Global Carbon Budget. 2021. Available online: https://www.globalcarbonproject.org/carbonbudget/ (accessed on 4 September 2022).
21. de Palma, A.; Vosough, S.; Liao, F. An Overview of Effects of COVID-19 on Mobility and Lifestyle: 18 Months since the Outbreak. *Transp. Res. Part A Policy Pract.* **2022**, *159*, 372–397. [CrossRef]
22. Priya, S.S.; Cuce, E.; Sudhakar, K. A Perspective of COVID-19 Impact on Global Economy, Energy and Environment. *Int. J. Sustain. Eng.* **2021**, *14*, 1290–1305. [CrossRef]
23. Crippa, M.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Solazzo, E.; Monforti-Ferrario, F.; Olivier, J.; Vignati, E. *Fossil CO_2 Emissions of All World Countries—2020 Report*; EUR 30358 EN; JRC121460; Publications Office of the European Union: Luxembourg, 2020; pp. 1–239. [CrossRef]
24. Eurostat. CO_2 Emissions from Energy Use Clearly Decreased in the Eu in 2020. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210507-1 (accessed on 29 December 2022).
25. Wang, X.; Si, C.; Gu, J.; Liu, G.; Liu, W.; Qiu, J.; Zhao, J. Electricity-Consumption Data Reveals the Economic Impact and Industry Recovery during the Pandemic. *Sci. Rep.* **2021**, *11*, 19960. [CrossRef] [PubMed]
26. Syed, A.A.; Kamal, M.A.; Tripathi, R. An Empirical Investigation of Nuclear Energy and Environmental Pollution Nexus in India: Fresh Evidence Using NARDL Approach. *Environ. Sci. Pollut. Res.* **2021**, *28*, 54744–54755. [CrossRef] [PubMed]
27. Skjærseth, J.B. Towards a European Green Deal: The Evolution of EU Climate and Energy Policy Mixes. *Int. Environ. Agreem. Polit. Law Econ.* **2021**, *21*, 25–41. [CrossRef]
28. Ciesielska-Maciągowska, D.; Klimczak, D.; Skrzek-Lubasińska, M. Central and Eastern European CO_2 Market—Challenges of Emissions Trading for Energy Companies. *Energies* **2021**, *14*, 1051. [CrossRef]
29. Kaveshnikov, N.Y. Analysis of the Influence of the European Parliament and the Council of the EU Exemplified by the EU Emissions Trading System Reform. *Mirovaya Ekon. Mezhdunarodnye Otnos.* **2021**, *65*, 21–32. [CrossRef]
30. Gerbeti, A. Market Mechanisms for Reducing Emissions and the Introduction of a Flexible Consumption Tax. *Glob. J. Flex. Syst. Manag.* **2021**, *22*, 161–178. [CrossRef]
31. Köhl, M.; Linser, S.; Prins, K.; Talarczyk, A. The EU Climate Package "Fit for 55"—A Double-Edged Sword for Europeans and Their Forests and Timber Industry. *For. Policy Econ.* **2021**, *132*, 102596. [CrossRef]
32. Sztorc, M. The Implementation of the European Green Deal Strategy as a Challenge for Energy Management in the Face of the COVID-19 Pandemic. *Energies* **2022**, *15*, 2662. [CrossRef]
33. Scheuing, H.; Kamm, J. The EU on the Road to Climate Neutrality—Is the 'Fit for 55' Package Fit for Purpose? *Renew. Energy Law Policy Rev.* **2022**, *10*, 4–18. [CrossRef]
34. Hammond, G.P. The UK Industrial Decarbonisation Strategy Revisited. *Proc. Inst. Civ. Eng.-Energy* **2022**, *175*, 30–44. [CrossRef]
35. Foster, W.; Azimov, U.; Gauthier-Maradei, P.; Molano, L.C.; Combrinck, M.; Munoz, J.; Esteves, J.J.; Patino, L. Waste-to-Energy Conversion Technologies in the UK: Processes and Barriers—A Review. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110226. [CrossRef]
36. Cadillo-Benalcazar, J.J.; Bukkens, S.G.F.; Ripa, M.; Giampietro, M. Why Does the European Union Produce Biofuels? Examining Consistency and Plausibility in Prevailing Narratives with Quantitative Storytelling. *Energy Res. Soc. Sci.* **2021**, *71*, 101810. [CrossRef]

37. Procházková, L.; Řezanka, T.; Nedbalová, L.; Remias, D. Unicellular versus Filamentous: The Glacial Alga Ancylonema Alaskana Comb. et Stat. Nov. and Its Ecophysiological Relatedness to Ancylonema Nordenskioeldii (*Zygnematophyceae*, *Streptophyta*). *Microorganisms* **2021**, *9*, 1103. [CrossRef] [PubMed]
38. Dębowski, M.; Zieliński, M.; Kazimierowicz, J.; Kujawska, N.; Talbierz, S. Microalgae Cultivation Technologies as an Opportunity for Bioenergetic System Development—Advantages and Limitations. *Sustainability* **2020**, *12*, 9980. [CrossRef]
39. Prasad, R.; Gupta, S.K.; Shabnam, N.; Oliveira, C.Y.B.; Nema, A.K.; Ansari, F.A.; Bux, F. Role of Microalgae in Global CO_2 Sequestration: Physiological Mechanism, Recent Development, Challenges, and Future Prospective. *Sustainability* **2021**, *13*, 13061. [CrossRef]
40. Meyer, M.T.; Itakura, A.K.; Patena, W.; Wang, L.; He, S.; Emrich-Mills, T.; Lau, C.S.; Yates, G.; MacKinder, L.C.M.; Jonikas, M.C. Assembly of the Algal CO_2-Fixing Organelle, the Pyrenoid, Is Guided by a Rubisco-Binding Motif. *Sci. Adv.* **2020**, *6*, eabd2408. [CrossRef]
41. Burlacot, A.; Dao, O.; Auroy, P.; Cuiné, S.; Li-Beisson, Y.; Peltier, G. Alternative Photosynthesis Pathways Drive the Algal CO_2-Concentrating Mechanism. *Nature* **2022**, *605*, 366–371. [CrossRef]
42. Dębowski, M.; Zieliński, M.; Kisielewska, M.; Kazimierowicz, J.; Dudek, M.; Świca, I.; Rudnicka, A. The Cultivation of Lipid-Rich Microalgae Biomass as Anaerobic Digestate Valorization Technology—A Pilot-Scale Study. *Processes* **2020**, *8*, 517. [CrossRef]
43. Siddiki, S.Y.A.; Mofijur, M.; Kumar, P.S.; Ahmed, S.F.; Inayat, A.; Kusumo, F.; Badruddin, I.A.; Khan, T.M.Y.; Nghiem, L.D.; Ong, H.C.; et al. Microalgae Biomass as a Sustainable Source for Biofuel, Biochemical and Biobased Value-Added Products: An Integrated Biorefinery Concept. *Fuel* **2022**, *307*, 121782. [CrossRef]
44. Grama, S.B.; Liu, Z.; Li, J. Emerging Trends in Genetic Engineering of Microalgae for Commercial Applications. *Mar. Drugs* **2022**, *20*, 285. [CrossRef]
45. Dębowski, M.; Dudek, M.; Zieliński, M.; Nowicka, A.; Kazimierowicz, J. Microalgal Hydrogen Production in Relation to Other Biomass-Based Technologies—A Review. *Energies* **2021**, *14*, 6025. [CrossRef]
46. Kazemi Shariat Panahi, H.; Dehhaghi, M.; Aghbashlo, M.; Karimi, K.; Tabatabaei, M. Shifting Fuel Feedstock from Oil Wells to Sea: Iran Outlook and Potential for Biofuel Production from Brown Macroalgae (*Ochrophyta; Phaeophyceae*). *Renew. Sustain. Energy Rev.* **2019**, *112*, 626–642. [CrossRef]
47. Torzillo, G. Photosynthesis Basic Principles to Optimize Growth of Microalgae Cultures Outdoors. *Environ. Biotechnol.* **2021**, *12*, 30–34.
48. Mehariya, S.; Goswami, R.K.; Verma, P.; Lavecchia, R.; Zuorro, A. Integrated Approach for Wastewater Treatment and Biofuel Production in Microalgae Biorefineries. *Energies* **2021**, *14*, 2282. [CrossRef]
49. Sharma, P.; Gujjala, L.K.S.; Varjani, S.; Kumar, S. Emerging Microalgae-Based Technologies in Biorefinery and Risk Assessment Issues: Bioeconomy for Sustainable Development. *Sci. Total Environ.* **2022**, *813*, 152417. [CrossRef]
50. Dębowski, M.; Zieliński, M.; Świca, I.; Kazimierowicz, J. Algae Biomass as a Potential Source of Liquid Fuels. *Phycology* **2021**, *1*, 105–118. [CrossRef]
51. Goswami, R.K.; Agrawal, K.; Verma, P. Phycoremediation of Nitrogen and Phosphate from Wastewater Using Picochlorum Sp.: A Tenable Approach. *J. Basic Microbiol.* **2022**, *62*, 279–295. [CrossRef]
52. Tang, J.; Liang, Q.; Li, C.; Huang, X.; Xian, X.; Li, J.; Shang, Z.; Pang, C.; Liu, Y.; Zhang, R. Application of Marine Algae in Water Pollution Control. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *966*, 12001. [CrossRef]
53. Costa, J.A.V.; Freitas, B.C.B.; Cruz, C.G.; Silveira, J.; Morais, M.G. Potential of Microalgae as Biopesticides to Contribute to Sustainable Agriculture and Environmental Development. *J. Environ. Sci. Health Part B* **2019**, *54*, 366–375. [CrossRef]
54. Peter, A.P.; Koyande, A.K.; Chew, K.W.; Ho, S.H.; Chen, W.H.; Chang, J.S.; Krishnamoorthy, R.; Banat, F.; Show, P.L. Continuous Cultivation of Microalgae in Photobioreactors as a Source of Renewable Energy: Current Status and Future Challenges. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111852. [CrossRef]
55. Chintagunta, A.D.; Zuccaro, G.; Kumar, M.; Kumar, S.P.J.; Garlapati, V.K.; Postemsky, P.D.; Kumar, N.S.S.; Chandel, A.K.; Simal-Gandara, J. Biodiesel Production From Lignocellulosic Biomass Using Oleaginous Microbes: Prospects for Integrated Biofuel Production. *Front. Microbiol.* **2021**, *12*, 2080. [CrossRef]
56. Shokravi, H.; Shokravi, Z.; Heidarrezaei, M.; Ong, H.C.; Rahimian Koloor, S.S.; Petrů, M.; Lau, W.J.; Ismail, A.F. Fourth Generation Biofuel from Genetically Modified Algal Biomass: Challenges and Future Directions. *Chemosphere* **2021**, *285*, 131535. [CrossRef]
57. Global Information. Global Microalgae Market—Industry Trends and Forecast to 2028. Available online: https://www.giiresearch.com/report/dbmr991581-global-microalgae-market-industry-trends-forecast.html (accessed on 29 December 2022).
58. Araújo, R.; Vázquez Calderón, F.; Sánchez López, J.; Azevedo, I.C.; Bruhn, A.; Fluch, S.; Garcia Tasende, M.; Ghaderiardakani, F.; Ilmjärv, T.; Laurans, M.; et al. Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. *Front. Mar. Sci.* **2021**, *7*, 1247. [CrossRef]
59. Roles, J.; Yarnold, J.; Hussey, K.; Hankamer, B. Techno-Economic Evaluation of Microalgae High-Density Liquid Fuel Production at 12 International Locations. *Biotechnol. Biofuels* **2021**, *14*, 1–19. [CrossRef] [PubMed]
60. Li, J.; Pan, K.; Tang, X.; Li, Y.; Zhu, B.; Zhao, Y. The Molecular Mechanisms of *Chlorella* Sp. Responding to High CO_2: A Study Based on Comparative Transcriptome Analysis between Strains with High- and Low-CO_2 Tolerance. *Sci. Total Environ.* **2021**, *763*, 144185. [CrossRef] [PubMed]
61. Mustafa, S.; Bhatti, H.N.; Maqbool, M.; Iqbal, M. Microalgae Biosorption, Bioaccumulation and Biodegradation Efficiency for the Remediation of Wastewater and Carbon Dioxide Mitigation: Prospects, Challenges and Opportunities. *J. Water Process Eng.* **2021**, *41*, 102009. [CrossRef]

62. Stewart, C.; Hessami, M.A. A Study of Methods of Carbon Dioxide Capture and Sequestration—The Sustainability of a Photosynthetic Bioreactor Approach. *Energy Convers. Manag.* **2005**, *46*, 403–420. [CrossRef]
63. Van Den Hende, S.; Vervaeren, H.; Boon, N. Flue Gas Compounds and Microalgae: (Bio-)Chemical Interactions Leading to Biotechnological Opportunities. *Biotechnol. Adv.* **2012**, *30*, 1405–1424. [CrossRef]
64. Chiu, S.Y.; Kao, C.Y.; Huang, T.T.; Lin, C.J.; Ong, S.C.; Chen, C.D.; Chang, J.S.; Lin, C.S. Microalgal Biomass Production and On-Site Bioremediation of Carbon Dioxide, Nitrogen Oxide and Sulfur Dioxide from Flue Gas Using *Chlorella* Sp. Cultures. *Bioresour. Technol.* **2011**, *102*, 9135–9142. [CrossRef]
65. Singh Chauhan, D.; Sahoo, L.; Mohanty, K. Maximize Microalgal Carbon Dioxide Utilization and Lipid Productivity by Using Toxic Flue Gas Compounds as Nutrient Source. *Bioresour. Technol.* **2022**, *348*, 126784. [CrossRef]
66. Nagappan, S.; Tsai, P.C.; Devendran, S.; Alagarsamy, V.; Ponnusamy, V.K. Enhancement of Biofuel Production by Microalgae Using Cement Flue Gas as Substrate. *Environ. Sci. Pollut. Res.* **2020**, *27*, 17571–17586. [CrossRef] [PubMed]
67. Kumar, K.; Banerjee, D.; Das, D. Carbon Dioxide Sequestration from Industrial Flue Gas by Chlorella Sorokiniana. *Bioresour. Technol.* **2014**, *152*, 225–233. [CrossRef] [PubMed]
68. Chakravarty, S.; Mallick, N. Carbon Dioxide Mitigation and Biodiesel Production by a Marine Microalga under Mixotrophic Mode by Using Transesterification By-Product Crude Glycerol: A Synergy of Biofuels and Waste Valorization. *Environ. Technol. Innov.* **2022**, *27*, 102441. [CrossRef]
69. de Morais, M.G.; Costa, J.A.V. Isolation and Selection of Microalgae from Coal Fired Thermoelectric Power Plant for Biofixation of Carbon Dioxide. *Energy Convers. Manag.* **2007**, *48*, 2169–2173. [CrossRef]
70. Sung, K.D.; Lee, J.S.; Shin, C.S.; Park, S.C.; Choi, M.J. CO_2 Fixation by *Chlorella* Sp. KR-1 and Its Cultural Characteristics. *Bioresour. Technol.* **1999**, *68*, 269–273. [CrossRef]
71. Chiu, S.Y.; Kao, C.Y.; Chen, C.H.; Kuan, T.C.; Ong, S.C.; Lin, C.S. Reduction of CO_2 by a High-Density Culture of *Chlorella* Sp. in a Semicontinuous Photobioreactor. *Bioresour. Technol.* **2008**, *99*, 3389–3396. [CrossRef]
72. Cheng, L.; Zhang, L.; Chen, H.; Gao, C. Carbon Dioxide Removal from Air by Microalgae Cultured in a Membrane-Photobioreactor. *Sep. Purif. Technol.* **2006**, *50*, 324–329. [CrossRef]
73. Dębowski, M.; Krzemieniewski, M.; Zieliński, M.; Kazimierowicz, J. Immobilized Microalgae-Based Photobioreactor for CO_2 Capture (IMC-CO_2PBR): Efficiency Estimation, Technological Parameters, and Prototype Concept. *Atmosphere* **2021**, *12*, 1031. [CrossRef]
74. Li, F.F.; Yang, Z.H.; Zeng, R.; Yang, G.; Chang, X.; Yan, J.B.; Hou, Y.L. Microalgae Capture of CO_2 from Actual Flue Gas Discharged from a Combustion Chamber. *Ind. Eng. Chem. Res.* **2011**, *50*, 6496–6502. [CrossRef]
75. Vunjak-Novakovic, G.; Kim, Y.; Wu, X.; Berzin, I.; Merchuk, J.C. Air-Lift Bioreactors for Algal Growth on Flue Gas: Mathematical Modeling and Pilot-Plant Studies. *Ind. Eng. Chem. Res.* **2005**, *44*, 6154–6163. [CrossRef]
76. Aslam, A.; Thomas-Hall, S.R.; Mughal, T.A.; Schenk, P.M. Selection and Adaptation of Microalgae to Growth in 100% Unfiltered Coal-Fired Flue Gas. *Bioresour. Technol.* **2017**, *233*, 271–283. [CrossRef] [PubMed]
77. Doucha, J.; Straka, F.; Lívanský, K. Utilization of Flue Gas for Cultivation of Microalgae *Chlorella* Sp. in an Outdoor Open Thin-Layer Photobioreactor. *J. Appl. Phycol.* **2005**, *17*, 403–412. [CrossRef]
78. Yadav, G.; Dubey, B.K.; Sen, R. A Comparative Life Cycle Assessment of Microalgae Production by CO_2 Sequestration from Flue Gas in Outdoor Raceway Ponds under Batch and Semi-Continuous Regime. *J. Clean. Prod.* **2020**, *258*, 120703. [CrossRef]
79. Dębowski, M.; Świca, I.; Kazimierowicz, J.; Zieliński, M. Large Scale Microalgae Biofuel Technology—Development Perspectives in Light of the Barriers and Limitations. *Energies* **2022**, *16*, 81. [CrossRef]
80. Tejada Carbajal, E.M.; Martínez Hernández, E.; Fernández Linares, L.; Novelo Maldonado, E.; Limas Ballesteros, R. Techno-Economic Analysis of Scenedesmus Dimorphus Microalgae Biorefinery Scenarios for Biodiesel Production and Glycerol Valorization. *Bioresour. Technol. Rep.* **2020**, *12*, 100605. [CrossRef]
81. Gifuni, I.; Pollio, A.; Safi, C.; Marzocchella, A.; Olivieri, G. Current Bottlenecks and Challenges of the Microalgal Biorefinery. *Trends Biotechnol.* **2019**, *37*, 242–252. [CrossRef]
82. Feng, P.; Xu, Z.; Qin, L.; Asraful Alam, M.; Wang, Z.; Zhu, S. Effects of Different Nitrogen Sources and Light Paths of Flat Plate Photobioreactors on the Growth and Lipid Accumulation of *Chlorella* Sp. GN1 Outdoors. *Bioresour. Technol.* **2020**, *301*, 122762. [CrossRef]
83. Shekh, A.; Sharma, A.; Schenk, P.M.; Kumar, G.; Mudliar, S. Microalgae Cultivation: Photobioreactors, CO_2 Utilization, and Value-Added Products of Industrial Importance. *J. Chem. Technol. Biotechnol.* **2022**, *97*, 1064–1085. [CrossRef]
84. Talaei, M.; Mahdavinejad, M.; Azari, R. Thermal and Energy Performance of Algae Bioreactive Façades: A Review. *J. Build. Eng.* **2020**, *28*, 101011. [CrossRef]
85. Sirohi, R.; Kumar Pandey, A.; Ranganathan, P.; Singh, S.; Udayan, A.; Kumar Awasthi, M.; Hoang, A.T.; Chilakamarry, C.R.; Kim, S.H.; Sim, S.J. Design and Applications of Photobioreactors—A Review. *Bioresour. Technol.* **2022**, *349*, 126858. [CrossRef]
86. Raeisossadati, M.; Vadiveloo, A.; Bahri, P.A.; Parlevliet, D.; Moheimani, N.R. Treating Anaerobically Digested Piggery Effluent (ADPE) Using Microalgae in Thin Layer Reactor and Raceway Pond. *J. Appl. Phycol.* **2019**, *31*, 2311–2319. [CrossRef]
87. Dineshkumar, R.; Sen, R. A Sustainable Perspective of Microalgal Biorefinery for Co-Production and Recovery of High-Value Carotenoid and Biofuel with CO_2 Valorization. *Biofuels Bioprod. Biorefin.* **2020**, *14*, 879–897. [CrossRef]
88. Onyeaka, H.; Miri, T.; Obileke, K.; Hart, A.; Anumudu, C.; Al-Sharify, Z.T. Minimizing Carbon Footprint via Microalgae as a Biological Capture. *Carbon Capture Sci. Technol.* **2021**, *1*, 100007. [CrossRef]

89. Paul, S.; Bera, S.; Dasgupta, R.; Mondal, S.; Roy, S. Review on the Recent Structural Advances in Open and Closed Systems for Carbon Capture through Algae. *Energy Nexus* **2021**, *4*, 100032. [CrossRef]
90. Sarat Chandra, T.; Maneesh Kumar, M.; Mukherji, S.; Chauhan, V.S.; Sarada, R.; Mudliar, S.N. Comparative Life Cycle Assessment of Microalgae-Mediated CO_2 Capture in Open Raceway Pond and Airlift Photobioreactor System. *Clean Technol. Environ. Policy* **2018**, *20*, 2357–2364. [CrossRef]
91. Xu, L.; Weathers, P.J.; Xiong, X.-R.; Liu, C.-Z. Microalgal Bioreactors: Challenges and Opportunities. *Eng. Life Sci.* **2009**, *9*, 178–189. [CrossRef]
92. Divya Kuravi, S.; Venkata Mohan, S. Mixotrophic Cultivation of *Monoraphidium* Sp. In Dairy Wastewater Using Flat-Panel Photobioreactor and Photosynthetic Performance. *Bioresour. Technol.* **2022**, *348*, 126671. [CrossRef]
93. Legrand, J.; Artu, A.; Pruvost, J. A Review on Photobioreactor Design and Modelling for Microalgae Production. *React. Chem. Eng.* **2021**, *6*, 1134–1151. [CrossRef]
94. da Silva, P.A.S.; Vargas, J.V.C.; Mariano, A.B.; Severo, I.A. Phycoremediation: Role of Microalgae in Waste Management and Energy Production. *Waste-Energy* **2022**, 511–537. [CrossRef]
95. Zhou, W.; Wang, J.; Chen, P.; Ji, C.; Kang, Q.; Lu, B.; Li, K.; Liu, J.; Ruan, R. Bio-Mitigation of Carbon Dioxide Using Microalgal Systems: Advances and Perspectives. *Renew. Sustain. Energy Rev.* **2017**, *76*, 1163–1175. [CrossRef]
96. Wang, B.; Lan, C.Q.; Horsman, M. Closed Photobioreactors for Production of Microalgal Biomasses. *Biotechnol. Adv.* **2012**, *30*, 904–912. [CrossRef]
97. Singh, D.; Goswami, R.K.; Agrawal, K.; Chaturvedi, V.; Verma, P. Bio-Inspired Remediation of Wastewater: A Contemporary Approach for Environmental Clean-Up. *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100261. [CrossRef]
98. Prabha, S.; Vijay, A.K.; Paul, R.R.; George, B. Cyanobacterial Biorefinery: Towards Economic Feasibility through the Maximum Valorization of Biomass. *Sci. Total Environ.* **2022**, *814*, 152795. [CrossRef] [PubMed]
99. Cui, X.; Yang, J.; Cui, M.; Zhang, W.; Zhao, J. Comparative Experiments of Two Novel Tubular Photobioreactors with an Inner Aerated Tube for Microalgal Cultivation: Enhanced Mass Transfer and Improved Biomass Yield. *Algal Res.* **2021**, *58*, 102364. [CrossRef]
100. Alami, A.H.; Alasad, S.; Ali, M.; Alshamsi, M. Investigating Algae for CO_2 Capture and Accumulation and Simultaneous Production of Biomass for Biodiesel Production. *Sci. Total Environ.* **2021**, *759*, 143529. [CrossRef] [PubMed]
101. Lim, Y.A.; Ilankoon, I.M.S.K.; Chong, M.N.; Foo, S.C. Improving Microalgae Growth and Carbon Capture through Micro-Size Bubbles Generation in Flat-Panel Photobioreactors: Impacts of Different Gas Sparger Designs on Mixing Performance. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113001. [CrossRef]
102. Meena, M.; Yadav, G.; Sonigra, P.; Shah, M.P. A Comprehensive Review on Application of Bioreactor for Industrial Wastewater Treatment. *Lett. Appl. Microbiol.* **2022**, *74*, 131–158. [CrossRef]
103. Xia, A.; Hu, Z.; Liao, Q.; Huang, Y.; Zhu, X.; Ye, W.; Sun, Y. Enhancement of CO_2 Transfer and Microalgae Growth by Perforated Inverted Arc Trough Internals in a Flat-Plate Photobioreactor. *Bioresour. Technol.* **2018**, *269*, 292–299. [CrossRef]
104. Zhao, Z.; Muylaert, K.; Szymczyk, A.; Vankelecom, I.F.J. Enhanced Microalgal Biofilm Formation and Facilitated Microalgae Harvesting Using a Novel PH-Responsive, Crosslinked Patterned and Vibrating Membrane. *Chem. Eng. J.* **2021**, *410*, 127390. [CrossRef]
105. Zhang, S.; Liu, Z. Advances in the Biological Fixation of Carbon Dioxide by Microalgae. *J. Chem. Technol. Biotechnol.* **2021**, *96*, 1475–1495. [CrossRef]
106. Duan, Y.; Guo, X.; Yang, J.; Zhang, M.; Li, Y. Nutrients Recycle and the Growth of Scenedesmus Obliquus in Synthetic Wastewater under Different Sodium Carbonate Concentrations. *R. Soc. Open Sci.* **2020**, *7*, 191214. [CrossRef]
107. Gulzar, A.; Gulzar, A.; Ansari, M.B.; He, F.; Gai, S.; Yang, P. Carbon Dioxide Utilization: A Paradigm Shift with CO_2 Economy. *Chem. Eng. J. Adv.* **2020**, *3*, 100013. [CrossRef]
108. Rodas-Zuluaga, L.I.; Castañeda-Hernández, L.; Castillo-Vacas, E.I.; Gradiz-Menjivar, A.; López-Pacheco, I.Y.; Castillo-Zacarías, C.; Iqbal, H.M.N.; Parra-Saldívar, R. Bio-Capture and Influence of CO_2 on the Growth Rate and Biomass Composition of the Microalgae Botryococcus Braunii and *Scenedesmus* sp. *J. CO2 Util.* **2021**, *43*, 101371. [CrossRef]
109. Ding, G.T.; Mohd Yasin, N.H.; Takriff, M.S.; Kamarudin, K.F.; Salihon, J.; Yaakob, Z.; Mohd Hakimi, N.I.N. Phycoremediation of Palm Oil Mill Effluent (POME) and CO_2 Fixation by Locally Isolated Microalgae: Chlorella Sorokiniana UKM2, *Coelastrella* Sp. UKM4 and Chlorella Pyrenoidosa UKM7. *J. Water Process Eng.* **2020**, *35*, 101202. [CrossRef]
110. Liu, X.; Chen, G.; Tao, Y.; Wang, J. Application of Effluent from WWTP in Cultivation of Four Microalgae for Nutrients Removal and Lipid Production under the Supply of CO_2. *Renew. Energy* **2020**, *149*, 708–715. [CrossRef]
111. Nguyen, L.N.; Truong, M.V.; Nguyen, A.Q.; Johir, M.A.H.; Commault, A.S.; Ralph, P.J.; Semblante, G.U.; Nghiem, L.D. A Sequential Membrane Bioreactor Followed by a Membrane Microalgal Reactor for Nutrient Removal and Algal Biomass Production. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 189–196. [CrossRef]
112. Zimmermann, A.W.; Buchner, G.A.; Schomäcker, R. Apples and Apples: A Shortcut Assessment Framework for Early-Stage Carbon Capture and Utilization Technologies Based on Efficiency, Feasibility, and Risk. *Energy Technol.* **2021**, *9*, 2000691. [CrossRef]
113. In-na, P.; Byrne, F.; Caldwell, G.S.; Lee, J.G.M. Techno-Economic Analysis of Living Biocomposites for Carbon Capture from Breweries. *Algal Res.* **2022**, *66*, 102781. [CrossRef]
114. Shahbaz, M.; Al-Ansari, T.; Aslam, M.; Khan, Z.; Inayat, A.; Athar, M.; Naqvi, S.R.; Ahmed, M.A.; McKay, G. A State of the Art Review on Biomass Processing and Conversion Technologies to Produce Hydrogen and Its Recovery via Membrane Separation. *Int. J. Hydrogen Energy* **2020**, *45*, 15166–15195. [CrossRef]

115. Chew, K.W.; Yap, J.Y.; Show, P.L.; Suan, N.H.; Juan, J.C.; Ling, T.C.; Lee, D.-J.; Chang, J.-S. Microalgae Biorefinery: High Value Products Perspectives. *Bioresour. Technol.* **2017**, *229*, 53–62. [CrossRef]
116. Wang, Y.; Yang, H.; Zhang, X.; Han, F.; Tu, W.; Yang, W. Microalgal Hydrogen Production. *Small Methods* **2020**, *4*, 1900514. [CrossRef]
117. Tsolcha, O.N.; Patrinou, V.; Economou, C.N.; Dourou, M.; Aggelis, G.; Tekerlekopoulou, A.G. Utilization of Biomass Derived from Cyanobacteria-Based Agro-Industrial Wastewater Treatment and Raisin Residue Extract for Bioethanol Production. *Water* **2021**, *13*, 486. [CrossRef]
118. Al-Dailami, A.; Ahmad, I.; Abdullah, N.; Koji, I.; Yuzir, A. Feasibility and Viability of Procuring Biohydrogen from Microalgae: An Emerging and Sustainable Energy Resource Technology. *J. Phys. Conf. Ser.* **2022**, *2259*, 12014. [CrossRef]
119. Dudek, M.; Dębowski, M.; Nowicka, A.; Kazimierowicz, J.; Zieliński, M. The Effect of Autotrophic Cultivation of Platymonas Subcordiformis in Waters from the Natural Aquatic Reservoir on Hydrogen Yield. *Resources* **2022**, *11*, 31. [CrossRef]
120. Kujawska, N.; Talbierz, S.; Dębowski, M.; Kazimierowicz, J.; Zieliński, M. Optimizing Docosahexaenoic Acid (DHA) Production by *Schizochytrium* Sp. Grown on Waste Glycerol. *Energies* **2021**, *14*, 1685. [CrossRef]
121. Ong, H.C.; Chen, W.-H.; Farooq, A.; Gan, Y.Y.; Lee, K.T.; Ashokkumar, V. Catalytic Thermochemical Conversion of Biomass for Biofuel Production: A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109266. [CrossRef]
122. Sekar, M.; Mathimani, T.; Alagumalai, A.; Chi, N.T.L.; Duc, P.A.; Bhatia, S.K.; Brindhadevi, K.; Pugazhendhi, A. A Review on the Pyrolysis of Algal Biomass for Biochar and Bio-Oil—Bottlenecks and Scope. *Fuel* **2021**, *283*, 119190. [CrossRef]
123. Kumar, M.; Oyedun, A.O.; Kumar, A. A Comparative Analysis of Hydrogen Production from the Thermochemical Conversion of Algal Biomass. *Int. J. Hydrogen Energy* **2019**, *44*, 10384–10397. [CrossRef]
124. Sivaramakrishnan, R.; Suresh, S.; Kanwal, S.; Ramadoss, G.; Ramprakash, B.; Incharoensakdi, A. Microalgal Biorefinery Concepts' Developments for Biofuel and Bioproducts: Current Perspective and Bottlenecks. *Int. J. Mol. Sci.* **2022**, *23*, 2623. [CrossRef] [PubMed]
125. Markou, G.; Monlau, F. Nutrient Recycling for Sustainable Production of Algal Biofuels. In *Biofuels from Algae*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 109–133. [CrossRef]
126. Kato, N. Production of Crude Bioplastic-Beads with Microalgae: Proof-of-Concept. *Bioresour. Technol. Rep.* **2019**, *6*, 81–84. [CrossRef]
127. Yong, J.J.J.Y.; Chew, K.W.; Khoo, K.S.; Show, P.L.; Chang, J.S. Prospects and Development of Algal-Bacterial Biotechnology in Environmental Management and Protection. *Biotechnol. Adv.* **2021**, *47*, 107684. [CrossRef]
128. Yang, W.; Dong, Y.; Li, J.; Fu, Q.; Zhang, L. Templating synthesis of hierarchically meso/macroporous N-doped microalgae derived biocarbon as oxygen reduction reaction catalyst for microbial fuel cells. *Int. J. Hydrogen Energy* **2021**, *46*, 2530–2542. [CrossRef]
129. Lan, L.; Li, J.; Feng, Q.; Zhang, L.; Fu, Q.; Zhu, X.; Liao, Q. Enhanced Current Production of the Anode Modified by Microalgae Derived Nitrogen-Rich Biocarbon for Microbial Fuel Cells. *Int. J. Hydrogen Energy* **2020**, *45*, 3833–3839. [CrossRef]
130. Thakkar, A.; Pienkos, P.T.; Nagle, N.; Dong, T.; Kruger, J.; Kumar, S. Comparative Study of Flash and Acid Hydrolysis of Microalgae (*Scenedesmus* Sp.) for the Recovery of Biochemicals and Production of Porous Biocarbon Nanosheets. *Biomass Convers. Biorefin.* **2022**, *1*, 1–10. [CrossRef]
131. Wen, X.; Du, K.; Wang, Z.; Peng, X.; Luo, L.; Tao, H.; Xu, Y.; Zhang, D.; Geng, Y.; Li, Y. Effective Cultivation of Microalgae for Biofuel Production: A Pilot-Scale Evaluation of a Novel Oleaginous Microalga *Graesiella* Sp. WBG-1. *Biotechnol. Biofuels* **2016**, *9*, 123. [CrossRef] [PubMed]
132. Supraja, K.V.; Behera, B.; Balasubramanian, P. Efficacy of Microalgal Extracts as Biostimulants through Seed Treatment and Foliar Spray for Tomato Cultivation. *Ind. Crops Prod.* **2020**, *151*, 112453. [CrossRef]
133. Ferreira, A.; Melkonyan, L.; Carapinha, S.; Ribeiro, B.; Figueiredo, D.; Avetisova, G.; Gouveia, L. Biostimulant and Biopesticide Potential of Microalgae Growing in Piggery Wastewater. *Environ. Adv.* **2021**, *4*, 100062. [CrossRef]
134. Martini, F.; Beghini, G.; Zanin, L.; Varanini, Z.; Zamboni, A.; Ballottari, M. The Potential Use of Chlamydomonas Reinhardtii and Chlorella Sorokiniana as Biostimulants on Maize Plants. *Algal Res.* **2021**, *60*, 102515. [CrossRef] [PubMed]
135. García, G.; Sosa-Hernández, J.E.; Rodas-Zuluaga, L.I.; Castillo-Zacarías, C.; Iqbal, H.; Parra-Saldívar, R. Accumulation of PHA in the Microalgae Scenedesmus Sp. under Nutrient-Deficient Conditions. *Polymers* **2020**, *13*, 131. [CrossRef] [PubMed]
136. Wang, K.; Mandal, A.; Ayton, E.; Hunt, R.; Zeller, M.A.; Sharma, S. Modification of Protein Rich Algal-Biomass to Form Bioplastics and Odor Removal. In *Protein Byproducts*; Academic Press: New York, NY, USA, 2016; pp. 107–117. [CrossRef]
137. Zeller, M.A.; Hunt, R.; Jones, A.; Sharma, S. Bioplastics and Their Thermoplastic Blends from Spirulina and Chlorella Microalgae. *J. Appl. Polym. Sci.* **2013**, *130*, 3263–3275. [CrossRef]
138. Mathiot, C.; Ponge, P.; Gallard, B.; Sassi, J.F.; Delrue, F.; Le Moigne, N. Microalgae Starch-Based Bioplastics: Screening of Ten Strains and Plasticization of Unfractionated Microalgae by Extrusion. *Carbohydr. Polym.* **2019**, *208*, 142–151. [CrossRef] [PubMed]
139. Irfan, M.F.; Hossain, S.M.Z.; Khalid, H.; Sadaf, F.; Al-Thawadi, S.; Alshater, A.; Hossain, M.M.; Razzak, S.A. Optimization of Bio-Cement Production from Cement Kiln Dust Using Microalgae. *Biotechnol. Rep.* **2019**, *23*, e00356. [CrossRef] [PubMed]
140. Arabian, D. Investigation of Effective Parameters on the Productivity of Biomass and Bio-Cement as a Soil Improver from *Chlorella vulgaris*. *Geomicrobiol. J.* **2022**, *39*, 781–790. [CrossRef]
141. Srinivas, M.K.; Alengaram, U.J.; Ibrahim, S.; Phang, S.M.; Vello, V.; Jun, H.K.; Alnahhal, A.M. Evaluation of Crack Healing Potential of Cement Mortar Incorporated with Blue-Green Microalgae. *J. Build. Eng.* **2021**, *44*, 102958. [CrossRef]

142. Biswas, J.K.; Kumar, A.; Biswas, S.; Shah, M.P.; Rodríguez-Couto, S. Win-Win Wastewater Phycoremediation: Coupled Carbon Sequestration and Heavy Metal Removal. In *An Integration of Phycoremediation Processes in Wastewater Treatment*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 529–548. [CrossRef]
143. Chen, Y.; Xu, C. Exploring New Blue Carbon Plants for Sustainable Ecosystems. *Trends Plant Sci.* **2020**, *25*, 1067–1070. [CrossRef] [PubMed]
144. Wedding, L.M.; Moritsch, M.; Verutes, G.; Arkema, K.; Hartge, E.; Reiblich, J.; Douglass, J.; Taylor, S.; Strong, A.L. Incorporating Blue Carbon Sequestration Benefits into Sub-National Climate Policies. *Glob. Environ. Chang.* **2021**, *69*, 102206. [CrossRef]
145. Babich, O.; Sukhikh, S.; Larina, V.; Kalashnikova, O.; Kashirskikh, E.; Prosekov, A.; Noskova, S.; Ivanova, S.; Fendri, I.; Smaoui, S.; et al. Algae: Study of Edible and Biologically Active Fractions, Their Properties and Applications. *Plants* **2022**, *11*, 780. [CrossRef]
146. Beerling, D.J.; Kantzas, E.P.; Lomas, M.R.; Wade, P.; Eufrasio, R.M.; Renforth, P.; Sarkar, B.; Andrews, M.G.; James, R.H.; Pearce, C.R.; et al. Potential for Large-Scale CO_2 Removal via Enhanced Rock Weathering with Croplands. *Nature* **2020**, *583*, 242–248. [CrossRef]
147. Dębowski, M.; Zieliński, M.; Rokicka, M.; Kupczyk, K. The Possibility of Using Macroalgae Biomass from Natural Reservoirs as a Substrate in the Methane Fermentation Process. *Int. J. Green Energy* **2015**, *12*, 970–977. [CrossRef]
148. Zhong, W.; Zhang, Z.; Luo, Y.; Qiao, W.; Xiao, M.; Zhang, M. Biogas Productivity by Co-Digesting Taihu Blue Algae with Corn Straw as an External Carbon Source. *Bioresour. Technol.* **2012**, *114*, 281–286. [CrossRef]
149. Li, X.; Lu, Y.; Li, N.; Wang, Y.; Yu, R.; Zhu, G.; Zeng, R.J. Mixotrophic Cultivation of Microalgae Using Biogas as the Substrate. *Environ. Sci. Technol.* **2022**, *56*, 3669–3677. [CrossRef] [PubMed]
150. Llamas, M.; Magdalena, J.A.; Tomás-Pejó, E.; González-Fernández, C. Microalgae-Based Anaerobic Fermentation as a Promising Technology for Producing Biogas and Microbial Oils. *Energy* **2020**, *206*, 118184. [CrossRef]
151. Bourgougnon, N.; Burlot, A.S.; Jacquin, A.G. Algae for Global Sustainability? *Adv. Bot. Res.* **2021**, *100*, 145–212. [CrossRef]
152. Wicker, R.J.; Kumar, G.; Khan, E.; Bhatnagar, A. Emergent Green Technologies for Cost-Effective Valorization of Microalgal Biomass to Renewable Fuel Products under a Biorefinery Scheme. *Chem. Eng. J.* **2021**, *415*, 128932. [CrossRef]
153. Zhao, Y.; Li, Q.; Gu, D.; Yu, L.; Yu, X. The Synergistic Effects of Gamma-Aminobutyric Acid and Salinity during the Enhancement of Microalgal Lipid Production in Photobioreactors. *Energy Convers. Manag.* **2022**, *267*, 115928. [CrossRef]
154. European Commission. *The EU Blue Economy Report 2020*; European Commission: Luxembourg, 2020; Available online: https://blueindicators.ec.europa.eu/ (accessed on 5 September 2022).
155. Li, S.; Li, X.; Ho, S.H. How to Enhance Carbon Capture by Evolution of Microalgal Photosynthesis? *Sep. Purif. Technol.* **2022**, *291*, 120951. [CrossRef]
156. Cardoso, L.G.; Lemos, P.V.F.; de Souza, C.O.; Oliveira, M.B.P.P.; Chinalia, F.A. Current Advances in Phytoremediation and Biochemical Composition of Arthrospira (*Spirulina*) Grown in Aquaculture Wastewater. *Aquac. Res.* **2022**, *53*, 4931–4943. [CrossRef]
157. Zieliński, M.; Dębowski, M.; Kazimierowicz, J. Outflow from a Biogas Plant as a Medium for Microalgae Biomass Cultivation—Pilot Scale Study and Technical Concept of a Large-Scale Installation. *Energies* **2022**, *15*, 2912. [CrossRef]
158. Al Jabri, H.; Taleb, A.; Touchard, R.; Saadaoui, I.; Goetz, V.; Pruvost, J. Cultivating Microalgae in Desert Conditions: Evaluation of the Effect of Light-Temperature Summer Conditions on the Growth and Metabolism of Nannochloropsis QU130. *Appl. Sci.* **2021**, *11*, 3799. [CrossRef]
159. Garbowski, T.; Pietryka, M.; Pulikowski, K.; Richter, D. The Use of a Natural Substrate for Immobilization of Microalgae Cultivated in Wastewater. *Sci. Rep.* **2020**, *10*, 7915. [CrossRef]
160. Zhang, Z.; Guo, L.; Liao, Q.; Gao, M.; Zhao, Y.; Jin, C.; She, Z.; Wang, G. Bacterial-Algal Coupling System for High Strength Mariculture Wastewater Treatment: Effect of Temperature on Nutrient Recovery and Microalgae Cultivation. *Bioresour. Technol.* **2021**, *338*, 125574. [CrossRef]
161. Piwowar, A.; Dzikuć, M. Bioethanol Production in Poland in the Context of Sustainable Development-Current Status and Future Prospects. *Energies* **2022**, *15*, 2582. [CrossRef]
162. Lin, Y.; Song, G.; Ling, H.; Ge, J.; Ping, W. Isolation of a High-Ammonium-Tolerant *Monoraphidium* Sp. and Evaluation of Its Potential for Biodiesel Production. *Process Biochem.* **2021**, *111*, 297–304. [CrossRef]
163. Yadav, G.; Mathimani, T.; Sekar, M.; Sindhu, R.; Pugazhendhi, A. Strategic Evaluation of Limiting Factors Affecting Algal Growth—An Approach to Waste Mitigation and Carbon Dioxide Sequestration. *Sci. Total Environ.* **2021**, *796*, 149049. [CrossRef] [PubMed]
164. Kujawska, N.; Talbierz, S.; Dębowski, M.; Kazimierowicz, J.; Zieliński, M. Cultivation Method Effect on *Schizochytrium* Sp. Biomass Growth and Docosahexaenoic Acid (DHA) Production with the Use of Waste Glycerol as a Source of Organic Carbon. *Energies* **2021**, *14*, 2952. [CrossRef]
165. Brzychczyk, B.; Hebda, T.; Fitas, J.; Giełżecki, J. The Follow-up Photobioreactor Illumination System for the Cultivation of Photosynthetic Microorganisms. *Energies* **2020**, *13*, 1143. [CrossRef]