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Algae, a biological purification tool for biogas upgrade: a review

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Abstract
One primary application of algae is in the production of biodiesel; however, they can also be employed as a means of removing carbon dioxide from biogas. Algae have recently attracted a lot of attention due to these advantages. Reducing carbon dioxide and possibly hydrogen sulfide concentrations improve biogas quality significantly. Because biogas is created as a mixture of methane gas and a significant amount of carbon dioxide, it needs to be cleaned (scrubbed) to create usable, ultra-pure biomethane. Algae offer a more environmentally friendly way to extract carbon dioxide from biogas and utilize it for photosynthesis whilst yielding itself for production of biodiesel. Algal culture systems for upgrading biogas present a viable substitute to traditional physical and/or chemical upgrading methods, as they are safer, more affordable, and less harmful to the environment hence contributing to a more sustainable circular economy. To completely explore the enormous potential of growing algae to capture carbon dioxide, more study is necessary. This review's objective is to present fact-based knowledge regarding algae's capacity to absorb carbon dioxide from biogas.

Keywords
Algae, Carbon dioxide, Biogas, Biological purification

Introduction

The photosynthetic capacity of algae is used in biogas scrubbing to eliminate contaminants from biogas, principally carbon dioxide (CO_2) and hydrogen sulfide (H_2S). This leaves behind a biogas that has been substantially cleansed and is mostly made up of biomethane (Das et al., 2022). A mixture of methane (50–75%), carbon dioxide (25–50%), trace amounts of nitrogen (2–8%), and other gases, such as water vapor, hydrogen sulfide, halogenated hydrocarbons, siloxanes, ammonia, and oxygen, are typically found in the biogas that is produced (Ramaraj and Dussadee 2015, Li et al., 2019). Biogas is synthesized by methanogens in an anaerobic decomposition of organic feedstocks, such as sewage, or manure or a combination of both in biodigester containers. As long as the primary components of any biomass are cellulose, hemicelluloses, proteins, fats, and carbohydrates, it can be utilized as a substrate for the production of biogas. However, biogas upgrading is the process whereby CO_2 and other impurities constituent in the produced biogas, are removed (or scrubbed) in order to yield higher volumes of biomethane (Deng et al., -

2020, Angelidaki et al., 2018). Bio-methane is typically made up of 95–99% CH_4, 1–6% CO_2 and 0.02–0.05% H_2S (Golmakani et al., 2022). Biogas upgrading is crucial for three main reasons. Firstly, impurities cause problems for the natural gas grid, appliances, and end users. Secondly, the removal of impurities raises the upgraded biomethane's calorific value, which lowers the treated biogas's density and satisfies the Wobble index, which is determined by dividing the volumetric lower calorific value by the square root of the gaseous fuel's relative density (Lyczko et al, 2017, Papurello et al., 2019). Lastly, when carbon dioxide is present, it makes it difficult to compress or liquefy bio-methane, for storage, transportation, and distribution in pressurized containers. Upgraded biomethane is a better source than natural gas (Awe et al., 2017). Biogas can be upgraded and purified in a variety of ways. Physiochemical technologies that require large amounts of energy and chemicals, like chemical scrubbing, condensation, catalytic conversion, membrane separation, and adsorption, have a negative impact on the process's sustainability from both an economic and environ-mental standpoint (Oruganti et al., 2023). The increasing need for energy and the usage of chemicals in various purification processes have made biological approaches a more attractive and superior substitute because they are more environmentally friendly (Atelge et al., 2021). Biological techniques involve the use of microbial consortia capable of consuming the present impurities and upgrading the biogas (Oruganti et al., 2023). Employing CO_2 contained in biogas as source of carbon for growth of micro-algae will lead to lower operational cost, thereby, yielding a biogas with finer methane content at cheaper costs.

CO_2 removal using photosynthetic biogas upgrade technique

The biogas to be upgraded is directly introduced into the reactor. Inside the reactor, photoautotrophic microorganisms consume the CO_2 in a carbon fixation cycle that produces glucose. This process can consume most of the CO_2 leaving about 2-6% CO_2 in the biogas, significantly enhancing the percentage of bio-methane. Common performers of this activity include *Spirulina* sp., *Chlorella* sp. and *Arthrospira* sp. (Munoz et al., 2015). Xia et al. (2015) described a two-way system of indirectly upgrading biogas as show in Figure 1, where direct and indirect biogas upgrade process technique was used with micro-algae. A carbonate solution traps CO_2 from the biogas in a bicarbonate form and the carbonate solution is regenerated (Xia et al., 2015). Microalgae produce biomass at low operating costs and have an amazing capacity to fix CO_2 (Ighalo et al., 2022). Microalgae were used by Posadas et al. to upgrade biogas and remove nutrients from a digester in an outdoor high-rate algal pond simultaneously. The potential of micro-algae as biological carbon fixers to aid in the growth of a circular economy and environmentally friendly coal-fired power plants was investigated by Yahya et al. (2020). Dasan et al. (2020) increased *Chlorella vulgaris*'s CO_2 fixation efficiency by optimizing critical culture parameters like pH and temperature.. Premaratne et al. (2021) assessed *Desmodesmus* sp.'s capacity to store CO_2 in flue gas under nitrogen element limitation conditions, and they used the biomass that was produced to prepare biofuel. According to Ding et al. (2020)), employing native microalgae species is a successful way to lower industrial CO_2 emissions and effluents from palm oil mills. Microalgae are an excellent option for carbon capture, which can also be applied to the manufacturing of biofuels, the treatment of wastewater, and other sectors of the economy. This is explained further in Table 1 where several carbon capture technologies are itemized and compared based on their benefits and limitations. Algal biomass can be used to produce a wide range of useful products. Thus, using biogas as a carbon source for algae cultivation has many benefits and is very promising for long-term algal scrub systems. Furthermore, the ability to remove CO_2 from biogas could make it a carbon neutral energy source, assisting in the control of worldwide anthropogenic CO_2 emissions, depending on the technologies employed (Golmakani et al., 2022).

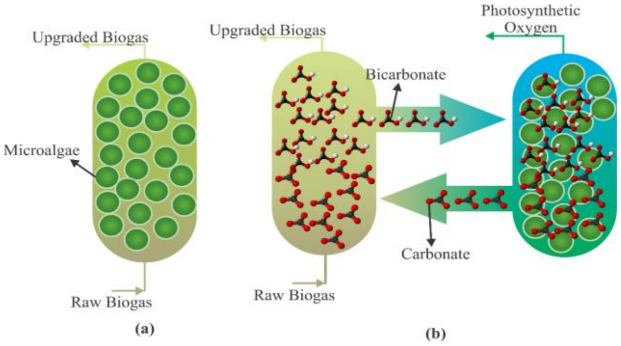

Figure 1. *The schematic flow chart of direct and indirect biogas upgrade system using microalgae (Culled from Xia et al., 2015)*

Algae in agriculture

Mostly aquatic, photosynthetic, and nucleus-bearing,

Table 1. *shows comparison of various carbon capture technologies*

Technique	Details of the Technique	Advantages	Limitations	Reference
Scrubbing using high pressure water	CO_2 is absorbed by water under increased pressure conditions.	Environmentally safer as a substitute for hazardous solvents. Thermally stable. High solubility of CO_2	Evaporation causes high loss of solvent. Equipment corrosion and cost intensive.	Ramaj and Dussadee, 2015, Starr et al., 2012, Ziobrowski et al., 2016.
Scrubbing using Chemical	Amine solution is used to absorb CO_2.			
Organic physical scrubbing	CO_2 is absorbed by Polyethylene glycol.			
Pressure Swing Adsorption	Activated carbon receives highly pressurized gas. The CO_2 is then released from the Carbon once the pressure is lowers.	Low waste generation	Energy inefficient	Siqueira et al., 2017, Bahrun et al, 2022.
Membrane separation technique	For pressurized biogas to pass through it a CO_2 selective membrane is used.	Increased packing density and efficiency due to the small installation needs.	Cost of membrane is high, fouling of membrane and high membrane surface area are needed.	Lei et al., 2020, Pasichnyk et al., 2023, Singh and Dhar, 2019.
Cryogenic method of separation	Biogas cools till CO_2 transforms to liquid making allowance for easy differentiation.	CO_2 capture efficiency is high.	High energy requirement for refrigeration. Solidified CO_2 builds up continuously on the heat exchanger periphery and could be removed.	Knapik et al., 2018, Song et al., 2019.
Microalgae-based carbon capture and use.	CO_2 Bioconversion into biofuels and other viable products through photosynthetic means.	Highly efficient in a wide range of CO_2 volumes. Faster growth rate than in plants. Co-production of food, biofuel, feed and value-added products, contact to a circular economy.	Economically cumbersome culture procedures. Flue gas components sensitivity (NOx, SOx) contamination and extreme culture conditions as pH, temperature, salinity.	Golmakani et al., 2022

algae are an order of organisms without true roots, stems, leaves, or specialized multicellular reproductive structures found in plants. Algae include seaweed, giant kelp, and pond scum (Andersen and Lewin, 2023). There are seven main types of algae, each with unique sizes, purposes, and colors. The divisions are as follows: Xanthophyta (yellow-green algae), Rhodophyta (red algae), Phaeophyta (brown algae), Pyrrophyta (fire algae), Chrysophyta (golden-brown algae and diatoms), and Euglenophyta (euglenoids) (Meeranayak, 2020). Micro-algae can manufacture extracellular substances, referred to as plant growth regulators, which affect the growth of plants. Microalgae such as *Coccomyxa onubensis* have shown antifungal and antibacterial activities in plants (Ferreira et al., 2023).

Algae as animal feed-stock

Numerous algae have been noted for having a high protein content, which makes them valuable for animal feed (Saadaoui et al., 2021). Significant human supplements like vitamins, amino acids, proteins, li-

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pids, polyunsaturated fatty acids, carbs, and antioxidants are abundant in algae's nutrient profile, as reported by multiple studies (Saadaoui et al., 2021, Barkia et al., 2019; Tibbetts et al., 2015). Global reports have indicated that algae are a promising feed source for animals. The results of various experiments, including one on chlorella, which was tested for chick development and demonstrated to be a nutrient supplement, are encouraging (El-Abd et al., 2017). There have been reports of several genera serving as possible feedstock for aquaculture facilities, including *Arthrospera, Tetraselmis, Chlorella, Dunaliella, Haematococcus, Nannochloropsis, Nitzschia, Navicula, Amphora*, and *Crypthecodinium* (Viegas et al., 2021).

Algae and Carbon neutrality

The scientific community is becoming increasingly interested in the necessity of carbon sequestration. Algae have the capacity to sequester more CO_2 than plants, with record efficiencies ranging from 10 to 50 times higher than those of terrestrial plants (Zhou et al., 2017, Onyeaka et al., 2021). Algae are able to absorb carbon dioxide from the air. Significant sequestration capacities have been reported for numerous algal species (Paul et al., 2020, Shukla et al., 2017, Moreira & Pires, 2016). In order to become carbon neutral, algae can serve as a sustainable carbon sink (Li et al., 2022, Fu et al., 2022).

Algae as bio-indicator of environment fitness

Growing algae in a variety of soil types may indicate the fertility and health of the soil (Abinandan et al., 2019). In agricultural land, the majority of the algae grow on top of the soil and serve as a sign of contaminated soil. Growing on contaminated waterways, phytoplanktons are a promising class of bio-indicators (Chandel et al., 2023). When heavy metals, including cadmium, lead, and mercury, are present in water bodies, they can be rapidly identified by looking for the growth of *Chlamydomonas reinhardtii* (Jaiswar and Chauhan 2017; Zayadan et al., 2020). Due to their enormous capacity to fix carbon dioxide from atmospheric air or flue gases and transform it into valuable bioproducts, algae have emerged as a viable scrub for biogas upgrading in modern times (Musa et al., 2019). Due to their quicker growth rates and ability to be cultivated in lakes, the ocean, and unfarmable land, algae have a number of potential advantages over higher plants. This includes reducing competition for food and feed (Ramaraj and Dussadee 2015). Algal application is generally ackno-wledged as one of the most effective bioengineering and biological purification techniques. This strategy is employed for multiple reasons: in comparison to plants, algae grow at the fastest rate; (ii) they have little to no effect on the world's food supply; (iii) they are specific for sequestering CO_2 without the need for gas separation, saving over 70% of total costs; (iv) they provide an excellent means of treating combu-stion gas exhausted with NOx and SOx; and (v) the high value of algae biomass, which can be used for feed, food, pharmaceutical chemicals, fertilizer, aquaculture, and biofuel and so on (Ramaraj and Dussadee 2015). For example, brown algae are real wonder plants when it comes to taking up carbon dioxide from the atmosphere. They thus have a significant impact on the atmosphere and climate because they outcompete terrestrial forests in this regard. They show that fucoidan, an algal mucus, is primarily in charge of this carbon removal and calculate that brown algae may be able to extract up to 550 million tons of carbon dioxide from the atmo-sphere annually (Buck-Wiese, 2022). Figure 2 illustrates the mechanism towards sustainnable biological carbon capture via micro-algae. The capacity of algae for bio-fixation has no negative environmental effects. Additionally, there are many

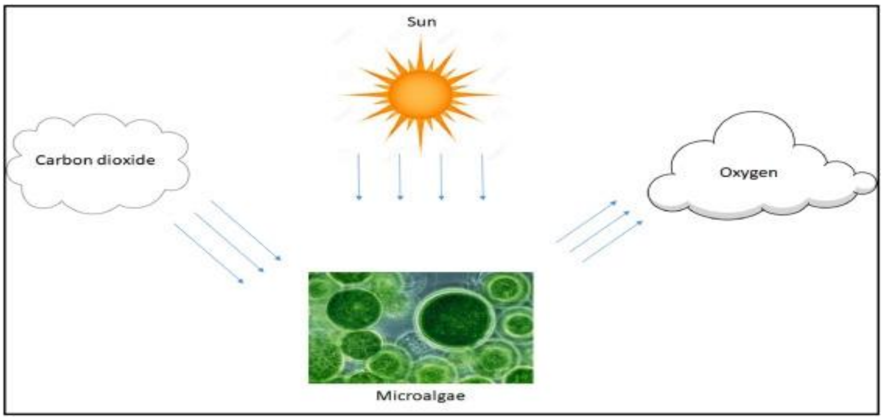

Figure 2
Mechanism towards sustainable biological carbon capture via micro-algae (culled from Onyeaka et al., 2021)

opportunities to improve performance, such as enhancing the photosynthetic capacities of algae strains to create a more circular economy, boost biomass yield, and serve as a source of biomass in and of themselves (Wilberforce et al., 2019; Alami et al., 2020; Moreira et al., 2023).

Biological purification using Algae

According to Singh and Dhar (2019), the term "algae" is commonly used to describe both prokaryotic blue-green algae called cyanobacteria and eukaryotic forms such as diatoms, green algae, and red algae. Efficient photosynthetic ability to obtain inorganic carbon from even very low atmospheric CO_2 concentrations makes them an attractive bio-system with potential as a CO_2 concentrating mechanism (CCM) (Singh and Dhar, 2019). The specialized multicellular reproductive structures found in plants are absent in algae. Algae and other avascular lower plants, such as lack of true roots, mosses, liverworts, hornworts and stems. Depending on their size, they are divided into two groups: macro-algae (multicellular) and micro-algae (unicellular). Since most algae need a wet or damp environment to thrive, they are commonly found around or within bodies of water (Andersen and Lewin, 2023). Three kinds of micro-algae are distinguished by their ability to tolerate CO_2: i) groups are CO_2-tolerant; they can tolerate moderate CO_2 levels of 5–20%; ii) groups are CO2-sensitive; low CO_2 levels of 2–5% inhibit them; and iii) groups are extreme CO_2-tolerant; they can tolerate very high CO_2 levels of 20–100% (Sadvakasova et al., 2023). Algae has been proven in several capacities that it has a wide removal rate of major pollutants in most environments. Table 2 below shows recent reports on micro-algae for up-cycling of wastewater and CO2 mitigation. The microalga *Chlorella* sp. MB-9, a possible strain that might absorb CO_2 for growth, could be enriched using desulfurized biogas (H_2S < 50 ppm) from the anaerobic digestion of swine wastewater, as demon-strated by Ramaraj and Dussadee in 2015. This team produced lipid and increased the amount of methane in the biogas by using oleaginous micro-algae to absorb CO_2. The capacity of a number of micro-algae to develop and produce lipid using CO_2 in biogas allowed for their identification (Ramaraj and

Table 2. *Recent reports on micro-algae for up-cycling of wastewater and CO_2 mitigation (Culled from Zabed et al., 2020)*

Micro-algae	Source of inoculum	Conditions	Pollutant elimination %
Botryococcus braunii	Pretreated wastewater from manufacturing of seafood 2.0 %	pH 6.7, Light intensity 49.5µmol photon m^{-2} s^{-1} with a 16:8 light and dark cycle, and temperature of 25 °C	Nitrate 91 %
Leptolyngbya sp.	Poultry droppings extract	24:0 ratio of light and dark cycle, temperature of 26 ± 2 °C, light intensity 200µmol photon m^{-2} s^{-1}	COD 94.1 % Nitrogen 88.1 % Phosphorus 97.3 %
Chlorella sp.	Effluents got from digesters in seafood factory/ CO_2 0.03 %	Light intensity 3000, 16:8 ratio of light and dark cycle with temperature of 25 °C	Nitrogen 94.6 % Phosphorus 77.3 %
Chlorella pyrenoidosa	Poultry excreta 25 % in BG-11 media	Light intensity 700 lx with a ratio of 9:15 light and dark cycle, 30 ± 1 °C temperature	TN 83.2 % NH_3–N 53.1 % TP 96.1 %
Desmodesmus sp. EJ8-10	Anaerobically-digested (DPE) piggery effluents	Light intensity 120 ± 2µmol photon m^{-2} s^{-1} with a 14:10 light and dark cycle, 27 ± 1 °C	NH^{4+}-N 90 % TN > 80 % PO^{43-}-P 100 %
Scenedesmus obliquus	Cattle wastewater	57µmol photon m^{-2} s^{-1} of light intensity with a 24:0 light and dark cycle, 21 °C temperature	COD 65–70 % NH_4^+ 98–99 % PO^{4-3} 69–77.5 % CO_2 fixation 327–547 mg/L^- d
Chlorella vulgaris	Municipal wastewater	Temperature of 25 °C, light intensity 90 ± 5µmol photon m^{-2} s^{-1}, with a 14:10 light and dark cycle	COD 75.3 % Ammonia 93.4 % Phosphate 90.5 %
Scenedesmus obliquus	Municipal wastewater	Temperature of 24 ±1°C, light intensity 90 ± 5µmol photon m^{-2} s^{-1}, with a 14:10 light and dark cycle	COD 74.9 % Ammonia 94.1 % Phosphate 91.3 % CO_2 bio-fixation rates 129.82 mg/L^- d

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Dussadee, 2015). Additionally, *Nannochloropsis* can utilize CO_2 from biogas that is created when tannery sludge is digested anaerobically. The cultivation of micro-algae under biogas to extract CO_2 and enhance methane enrichment in the biogas produced results that de-monstrated a 27% scrubbing efficiency, up from 30% (Ramaraj and Dussadee 2015). By lowering improve the efficiency CO_2 content and increasing methane content, microalgae's bio-capture of CO_2 can be used to enhance the efficiency of biogas. According to Kao et al., when aerated with desulfurized biogas (H_2S < 50ppm) obtained from the anaerobic digestion of swine wastewater, *Chlorella* sp. MB-9 used carbon dioxide for development. Chen et al., 2020 reported that *Chlorella sorokiniana* produced 5.45 g/L of biomass with a protein productivity of 0.27 g/L d when grown in 50% (v/v) diluted swine wastewater, demonstrating the efficient removal of pollutants. Singh et al. (2020) reported that *Chlorella pyrenoidosa* efficiently treated 25% diluted poultry wastewater, producing biomass, carbohydrates, protein, lipid, and chlorophyll at concentrations of 2.5 g/L, 0.64 g/L, 1.02 g/L, 0.49 g/L, and 20 µg/mL. It's interesting to remember that Qu et al. (2020) reported on *Chlamydomonas* sp. QWY37's capacity for bioremediation in non-sterilized, non-diluted swine wastewater. The micro-algae exhibited a reduction of 81% in chemical oxygen demand (COD), 96% in total nitrogen (TN), and roughly 100% in total phosphorus (TP), all while producing 7 g/L of biomass and 944 mg/L of daily carbohydrate productivity. Li et al., 2021 treated anaerobically digested (DPE) piggery effluents with microalga *Desmodesmus* sp. EJ8-10. The efficiency of removal of phosphate, ammonia, and TN were 90%, >80%, and almost 100%, in that order. The micro-algae grown in DPE had a final biomass of 0.15 - 0.35 g/L and a lipid content of 19-28%. Cheirsilp et al. (2022) recently cultivated *Haematococcus* sp. to value wastewater from seafood processing. According to their observations, micro-algae could remove COD, TP, and TN by 50%, 100%, and 100%, respectively, with 1.33 g/L of microalgal biomass and 30.81% lipid content. *Scenedesmus obliquus* demonstrated a CO_2 mitigation rate of 327-547 mg/L and a biomass productivity of 213-358 mg/L. According to Chaudhary et al. (2018), the daily maximum CO_2 mitigation rate by *Chlorella vulgaris* ATCC 13482 was 140.91 mg/L when grown in municipal wastewater aerated with 5% CO_2 in air at a flow rate of 1.4 L/min. The daily maximum CO_2 mitigation rate by *Scenedesmus obliquus* FACHB was marginally lower at 129.82 mg/L. Hariz et al., (2019) grew the native microalga *Chlorella* sp. UKM2 using CO_2 and palm oil mill effluent. The micro-alga fixed CO_2 at a rate of 0.829 g/L Day and removed 48%, 85%, and 86% of the COD, TP, and TN, respectively, after operating for 15 days. 12.435 g/L of CO_2 was recovered in total. In a different study, Kassim and Meng (2017) examined the CO_2 bio-fixation by *Tetraselmis suecica* and *Chlorella* sp. using various elevated CO_2 concentrations. Using 0.04%, 5%, 15%, and 30% CO_2, the impact of CO_2 concentration on the kinetics of micro-algae growth, bio-fixation, and its chemical composition was ascertained. Investigations were also conducted into the relationship between the initial pH value variation and the CO_2 concentration toward the cultivation medium. Different levels of tolerance to CO_2 concentration were demonstrated by two micro-algae. When *Chlorella* sp. was cultivated with 5 and 15% CO_2, respectively, the maximum biomass production and bio-fixation of 0.64 g L^{-1} and 96.89 mg L^{-1} d $^{-1}$ were attained. In contrast, *T. suecica* produced the highest amount of biomass (0.72 g L^{-1} and 111.26 mg L^{-1} d $^{-1}$) when grown in environments with 15 and 5% CO_2, respectively. The CO_2-infused cultivation medium had a pH range of 7.5 to 9, which is perfect for micro-algae development. This study indicates that *T. suecica* and *Chlorella* sp. are useful algae for CO_2 bio-fixation (Kassim and Meng, 2017). Due to their greater capacity for photosynthetic respiration and carbon dioxide sequestration, *Chlorella sorokiniana* and *Scenedesmus obliquus* were used in application of a micro-algae CO_2 capturing system (Sreelakshmi et al., 2021). *Scenedesmus obliquus* was found to grow more quickly in the purified condition, which eventually leads to improved CO_2 scrubbing. Out of the purified biogas, *Scenedesmus obliquus* removed 50% of the CO_2, while *Chlorella sorokiniana* was only able to sequester 23%. Research indicates that *Scenedesmus* sp. can sequester up to 80% of CO_2, while *Chlorella* sp. can scrub up to 40%. Sumardiono et al. developed a photobioreactor system that uses *Nannochloropsis* to grow micro-algae and purify biogas. The setup decreased the concentration of CO_2 in biogas by 27% and consequently enhanced micro-algae biomass (Sumardiono et al., 2014). *Chlorella* sp. reduced CO_2 and H_2S content to 97.07% and 100% respectively (Mann et al., 2009). Methane content can be increased and CO_2 content can be decreased in biogas with the use of microalgae's bio-capture of CO_2.

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Environmental factors that affect micro-algal culturing for capture of carbon dioxide

Carbon dioxide removal rate by micro-algal cells depends on several factors such as gas aeration rate, CO_2 concentration, light spectrum intensity, pH, temperature, photo period and nutrients availability (Thomas et al., 2016, Fernandez et al., 2012). Figure 3 illustrates several factors which enhance CO_2 removal rate of micro-algae an its cultivation and growth.

Light. One of the main energy sources that microalgae use for photosynthesis is light. Light quantity, then, is the amount of illumination, whether it comes from artificial or natural sources. As anticipated, increasing light intensity causes the micro-algae biomass in the culture to grow until it reaches a saturation point, at which point the rate of photosynthesis reaches its maximum level (Gani et al., 2019). However, photoinhibition may result from exposure to excessive amounts of light (Gani et al., 2019, Kumar et al., 2018). Reactive oxygen species that are damaging to microalgae cells and indirectly lower biomass productivity are the cause of photoinhibition. *Scenedesmus* sp. produced microalgae at a rate that was roughly 45% higher than at a single wavelength of 400–700 nm white light, according to Kim et al. (Kim et al., 2013). Green microalgae *Scenedesmus obliquus* 276.7 was grown by Sforza et al. in BG11 medium at 23°C, with the best growth conditions achieved at 150 μmol m^{-2} s^{-1}. Up until the point of saturation, its growth rate increased linearly with an increase in light intensity (Sforza et al., 2014).

Photoperiod. The length and pattern of exposure, or photoperiod the amount of time an organism is exposed to light each day, is another crucial factor to take into account. In terms of duration, it also refers to light exposure, with minimum and maximum values of 0:24 and 24:0 hours, respectively. Since photoperiod directly affects the efficiency of photosynthesis of micro-algae in the culture, it is just as important as light intensity (Gani et al., 2019). The impacts of different photoperiods have been investigated in order to develop the best exposure plan. Three examples of light/dark cycles are the 12/12 (Nithiya et al., 2017, Duarte et al., 2017), 16/8 (Aslam et al., 2017), and 14/10 (Kumari et al., 2014) hour cycles. The type and species of strain will determine the ideal photoperiod for microalgae. Apart from that, variations in the necessary optimal photoperiod may also be attributed to the natural habitat of micro-algae. Few studies have examined how photoperiod affects the growth rate and productivity of specific algae, including *Chlorella vulgaris, Neochloris conjuncta, Botryococcus braunii, Scenedesmus* sp.*, and Eustigmatophyte Nannochloropsis* sp. (Krzemińska et al., 2014, Wahidin et al., 2013). Krzemińska and colleagues found that while *Neochloris conjuncta* was more tolerant at 12:12 hours in terms of growth rate and biomass production, continuous illumination more effectively stimulated the growth of

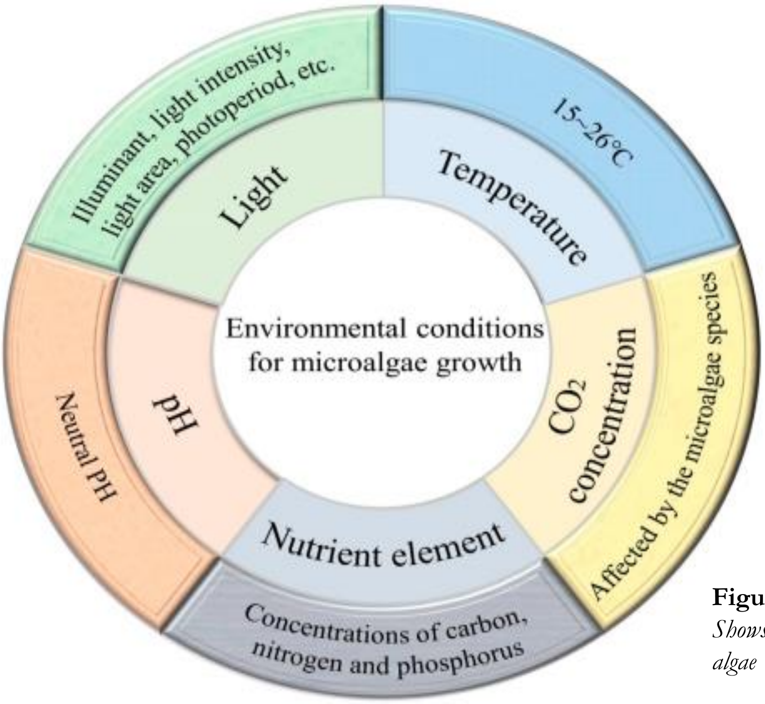

Figure 3
Shows several factors which enhance CO2 removal rate of micro-algae an its cultivation and growth (Culled from Li et al., 2023)

Botryococcus braunii and *Scenedesmus obiqus* (Krzemińska et al., 2014). After analyzing the effects of photoperiod on *Nannochloropsis* sp. for eight days, Wahidin et al. (2013) discovered that the optimal light exposure occurs during 18:6 hours, resulting in a maximum cell concentration of 6.5 × 107 cells/mL. Howerer, unlike other microalgae species, *Chlorella vulgaris* has a completely distinct photoperiod. Due to their natural habitat in wetlands, *Chlorella vulgaris* maximize their biomass when exposed to a photoperiod of 16:8 hours with 62.5 µmol m^{-2} s^{-1} of illumination (Gani et al., 2019). Rai et al. (2017) observed that prolonged exposure to light, with a 24/0 light/dark cycle, can cause strain on the organism; thus, dark periods are necessary for the proper metabolic activity of algae

Temperature. Microalgae's cell size and biochemical makeup are greatly influenced by temperature. Variations in temperature have the potential to severely impair the growth of microalgae cells, rendering them incapable of proliferating (Gani et al., 2019). According to Zhao et al., the range of 15 to 26 °C was ideal for the growth of the most prevalent micro-algae (Zhao et al., 2014). Micro-algae are often irreversibly damaged by high temperatures. Table 3 highlights the optimal temperatures for different species of micro-algae. *Chlorella pyrenoidosa* M18 was found by Sachdeva et al. to be capable of withstanding temperatures as high as 47 °C, with the maximum average growth rate occurring at 37 °C (Sachdeva et al., 2016).

Table 3. *The optimal growth temperature for different species of micro-algae*

Microalgae	Growth medium	Growth temperature (°C)	Specific growth (d^{-1})	Reference
Chlorella pyrenoidosa M18	BG 11	37	0.70	Sachdeva et al., 2016
Thermosynechococcus elongatus PKUAC-SCTE542	BG 11	55	0.22	Liang et al., 2019
Chlorogleopsis sp.	BG 11	50	0.14	Li et al., 2023
Chlorella sp. MT-IS	Artificial seaweed	30	Approximately 0.80	Li et al., 2023
Nannochloropsis oculata	Modified Fitzgerald	30	1.60	Li et al., 2023

Salinity. The presence of salt in the water necessary for the growth of microalgae is referred to as salinity. As anticipated, freshwater algae use a lower salinity concentration than marine algae (Harris et al., 2022, Gani et al., 2019). Since salinity can have an impact on algal growth, salinity is another essential parameter that needs to be measured (Gani et al., 2019). Because it can change the structure of their cells, freshwater algae are harmed when exposed to high salinities. Over-salinity reduces the biomass productivity of microalgae and prevents photosynthesis (Gani et al., 2019).

pH. Most micro-algae are suitable for cultivation under neutral pH conditions (Hosseini et al., 2018), with exceptions, such as *Chlorococcum* could live in pH 4.0, and *Spirulina* at pH 11.0 (Razzak et al., 2015). Razzak et al. discovered that *Nannochloropsis oculata*) grew well between medium pH 5.5 and 6.5 (Razzak et al., 2015).

Nutrient Element. The building blocks of micro-algae's cell synthesis include carbon, nitrogen, and phosphorus, which are also crucial nutrients for the biomass growth. To some extent, the photosynthesis of micro-algae is influenced by the species, morphology, and quality of the nutrients. Carbon–nitrogen ratio (C/N) is among the important factors affecting carbon fixation efficiency, biomass accumulation and productivity of value-added components (Li et al., 2020, 2018, Razzak et al., 2017).

Carbon dioxide concentration. The capability of different micro-algae to tolerate CO_2 is different. Even though certain micro-algae have great CO_2 tolerance and can grow across most of the CO_2 con-

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centration range, the optimal growth concentration is determined. Some micro-algae can grow normally at low concentrations of CO_2, while some will only show high growth rates at high concentrations of CO_2. Either a too high or too low CO_2 concentration reduces the CO_2 fixation efficiency and the biomass yield (Anjos et al., 2013). However, high CO_2 concentrations can lower pH causing impeded cell growth (Li et al., 2023).

Prospects of an Algal carbon dioxide scrub system

Researchers found that micro-algae have a CO_2 fixation rate of 0.73 to 2.22g $^{-1}$ L^{-1} day, or roughly 12 to 15% of atmospheric CO_2, which is 10 to 50 times higher than other terrestrial plant species (Pourjamshidian et al., 2019, Cheah et al., 2015). Seeing that assimilation of CO_2 increases the growth of micro-algae, in turn increasing the carboxylase activity leading to photosynthetic activity, several studies have taken interest in the workability of algae as a carbon scrub for upgrade of biogas (Thomas et al., 2016). The development of *Spirulina* sp. microalgal biomass and lipid production during cultivation were assessed in a study conducted by Orugani et al. (2023). Air and biogas from an anaerobic digester were fed to *Spirulina*. When compared to an air supply, it was found that the reactor sparged with biogas had a sharp rise in production. The amount of lipid in the reactor that was sparged with biogas increased significantly. The increasing availability of CO_2 that is promoting algae growth may be the cause of this increase in biomass production. Algal carbon capture is a biological method that merits more investigation to rival current carbon capture technologies (Paul et al., 2020). Table 4 itemizes algal scrub system using named micro-algae indicating their CO_2 and CH_4 removal rates. Notably, algae can extract biofuel and trans-form carbon dioxide (CO_2) into biomass. They are also a useful source of bioenergy (Jalilian et al., 2020, Saifuddin et al., 2015, Hernandez-Mireles et al., 2014).

Table 4. *Shows the potential of algal scrub systems*

Microalgal species	In/Out -door	System	CO_2 % Removal	CH_4 % Removal	Reference
Chlorella sp.	Outdoor	HRAP	95	94	Hoyos et al., 2024
Chlorella vulgaris	Outdoor	HRAP	55	80.4	Hoyos et al., 2024
Scenedesmus obliquus	Outdoor	EPB	62	82.6	Velasco et al., 2023
Neochloris oleoabundans	Outdoor	EPB	54	80.0	Velasco et al., 2023

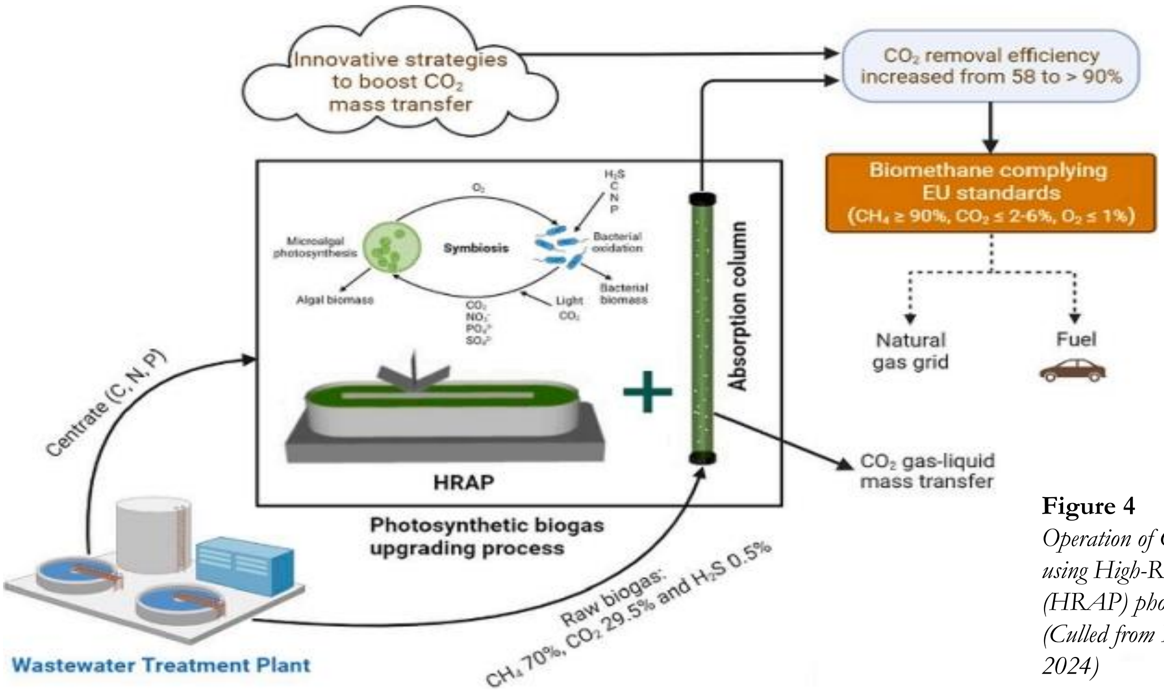

Figure 4
Operation of CO_2 removal using High-Rate Algal Pond (HRAP) photobioreactor (Culled from Hoyos et al., 2024)

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Combinations of microalgae and bacteria have also demonstrated the effective CO_2 removal capabilities of a strong and stable photosynthetic population. Velasco et al., 2023, studied the performance of an outdoor pilot-scale system made up of a high-rate algal pond planted with a microalgal-bacterial consortia. The consortium used biogas and organic leachate, which is obtained from the anaerobic hydrolysis of food waste, as sources of CO_2 and nutrients, respectively. This is as shown in Figure 4 where high-rate algal pond (HRAP) photobioreactor is used for CO_2 removal. Biogas had removal efficiencies of 80.0% and 99.9% for CO_2 and H_2S, respectively, resulting in a methane content of about 55 vol%. Along with certain microalgae atmospheric CO_2, the microbial mixture included *Picochlorum* sp., *Pseudanabaena* sp., *Spirulina* sp., and *Nitzschia* sp. (Velasco et al., 2023; Hoyos et al., 2024)..

Conclusions

Biogas, a combination of methane, carbon dioxide, and other uncommon gases, is produced by anaerobic digestion systems. The carbon dioxide that is present in this process can be efficiently used by micro-algae to improve their photosynthetic and heterotrophic capabilities, which raises the quality of bio-methane produced while also removing CO_2 from the atmosphere and supports the circular economy idea. Micro-algae are a good choice for scrubbers because they are readily available, can withstand high pH and CO_2 levels, and are simple to harvest. This review provided evidence-based information about the potential of algae to sequester carbon dioxide from biogas. In order to reap environmental benefits of using micro-algae for biological purification processes, novel emerging technologies can be employed to enhance this upgrade technology.

Declarations

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that this review does not report or on involve animals, humans, human data.

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