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CO_2 bioremediation by microalgae in photobioreactors: impacts of biomass and CO_2 concentrations, light, and temperature.

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ABSTRACT

Microalgae have the potential to recycle and bioremediate CO_2 and also produce chemical energy in the form of biomass. The potential production of renewable energy and high value products (i.e. carotenoid, antioxidants and polyunsaturated fatty acids) make large scale microalgal cultivation an attractive application. To achieve high productivity all microalgae cultures require CO_2 addition. Various microalgae species have shown different capabilities to bioremediate CO_2. This review article reports biomass concentrations, biomass productivities, and CO_2 fixation rates of several microalgae and cyanobacteria species under different input CO_2 concentrations. The effect of important factors such as photo-bioreactor, temperature, light intensity on CO_2 removal have also been discussed.

***Keywords*:** Carbon dioxide; microalgae; biomass; temperature; light; photobioreactor.

1. Introduction

Conventional power stations emit 344 to 941 kg of carbon dioxide (CO_2) per MWh at capacities of 400-1200 MW [1]. Power stations represents roughly 7% of total emitted CO_2 into the atmosphere [2-4]. In general the power plant flue gases consist of 10-20% CO_2 [2, 5], are largely alkaline, with an output

temperature of around 120^{0}C [6, 7]. The CO_2 remediation is accomplished in three main methods; (1) chemical reaction-based strategies including washing with alkaline solutions [8, 9], multi-walled carbon nanotubes [10], and amine coated activated carbon [11-13], (2) direct injection to underground [14], or to the ocean [15], and (3) biological CO_2 mitigation, with CO_2 being biologically converted to organic matters [16, 17].

Microalgae are now under investigation as one of the most promising bioremediation alternatives for many sources of CO_2 emissions [18]. The authors have selected the term 'bioremediation' as we are discussing temporary fixation of CO_2 in the microalgal biomass, akin to other bioremediation processes (usually soil-based mineral bioremediation). Microalgae have the capability to remove 10 to 50 times more CO_2 from CO_2 sources (such as flue gases) than terrestrial plants [2, 19], primarily due to more chlorophyll per unit area. Microalgae can utilize CO_2 from different sources: i) atmospheric CO_2; ii) industrial exhaust gases, and; iii) CO_2 in the form of soluble carbonates (e.g $NaHCO_3$ and Na_2CO_3) [20]. Bicarbonate (HCO_3^-) is the predominant form of dissolved inorganic carbon (DIC) in seawater (pH = 8) [21], and the utilization of either CO_2 or HCO_3^- as the preferred carbon source for photosynthesis and as effective co-supplementation has been found to be species dependent [22]. For example, Hsueh et al., [23] and Su et al., [24] showed that growth rate of *Thermosynechococcus sp* increased with increasing DIC, while in Moheimani's study [21] growth rate and lipid productivity of *Chlorella sp* and *Tetraselmis suecica* CS-187 were higher under pure CO_2 or flue gas carbon sources as compared with $NaHCO_3$. Comparing algae CO_2 fixation rates under different carbon sources and experimental conditions is a challenging task, particularly for different carbon sources (direct CO_2 or DIC), a wide pH range (5.5 to 12), lighting regimes, and temperatures (18 to 40^{0}C) [21-24] . Furthermore, the differing objectives of present algae research (biomass, lipid and/or carbohydrate productivity, or CO_2 bioremediation efficiency of different strains etc.) necessitate integrated projects that explore optimized conditions for various growth parameters and bioremediation efficacy. At present, algae is cultivated for different purposes such asvarious renewable fuels (bioethanol [16, 25-27], biodiesel [28], biomethane, biohydrogen [29-31], etc.) and nutrition [25, 27, 32-35] vitamins [27, 36, 37], minerals [25, 37], proteins [25, 27, 36, 38], fats [38,

39], sugars [38, 40], antioxidant [16, 41], animal feeds [16, 42, 43], cosmetics [27, 43-45], pharmaceuticals [16, 35, 36, 46-57], chemicals [16, 25, 27, 44], bioactive neutraceuticals [58-60], biofertilisers [27, 61] and bioremediation [5]. Some microalgae also produce useful carotenoids [36, 43], phycobilins [36], polyketides [43], mycosporine-like amino acids [43], glycerol [36], steroids [43], tocopherol [36], lectins [43], astaxanthin [36], canthaxanthin [36], functional sulphated polysaccharides [25, 36, 43], zeaxanthin [25], halogenated compounds [43], and some toxins [43]. It is clear that multi-parameter optimization techniques are required to determine the most appropriate algae strains, growth conditions, and input parameters suitable to a broad range of industrial scale algae cultivation [62-65]. Yet, biomass productivity plays a significant role in any microalgae production system, and the production of many target constituents is dependent on primary biomass productivity (including the production of lipids, hydrocarbons, polysaccharides and other energy storage compounds).

2. Photobioreactor cultivation systems and mass transfer

Controlling microalgal production to a very high degree requires closed photobioreactor cultivation systems, and they offer significant productivity advantages including high production efficiency and biological contamination minimization [66-69]. However, their technical complexity generally results in relatively high CAPEX and OPEX [37, 69, 70]. Production aims using photobioreactors are generally to maximize biomass productivity and to minimize production costs per unit of output [37, 66, 71, 72]. As biomass productivity needs to remain high to offset high production costs, culture mass transfer must be efficient, and mass transfer limitations are a common issue in closed system photobioreactors [37, 70, 72, 73]. The design of a photobioreactor should aim to maximize CO_2 mass transfer rates, and the "two-film theory" states that CO_2 mass transfer from the gas-phase to the cell-phase consists of different stages. The gas-liquid stage determines the mass transfer of CO_2, and is given by: $N_{CO2}= k_L\alpha\ (C_{CO2}L^*- C_{CO2}L)$, where k_L is the liquid-phase mass transfer coefficient, α is the specific available area for mass transfer, $C_{CO2}L^*$ is the CO_2 concentration in the liquor that equilibrates the partial pressure on the gas side, and $C_{CO2}L$ is the

CO_2 concentration in the liquor. Jacob-Lopes et al., [74] introduced several methods to increase N_{CO2} by raising k_L and/or α such as microporous hollow-fiber membranes, air-lift bubble columns, stirring, gas injection methods and gas recirculation [75]. Fig. 1 illustrates three types of basic photobioreactors ; (i) without inner column (i.e. a bubble column), (ii) with a centric-tube column, and (iii) with a porous centric-tube column [76]. As shown in Table 1 the maximum biomass concentration in photobioreactors without an inner column, with centric-tube column and with porous centric tube are 2.369, 2.534 and 3.461g L^{-1}, respectively. This result shows that maximum biomass concentration in the porous centric-tube photo-bioreactor is greater by 46 % and 37 % in comparison with those in the bubble column PBR and in the centric-tube PBR, respectively. Furthermore, the specific growth rate of *Chlorella sp. NCTU-2* was also improved in the porous centric-tube. Additionally, the CO_2 removal efficiency enhanced in the porous centric-tube photo-bioreactor by 45 and 52% compared to those in the bubble column and centric-tube PBRs, respectively (Table 1) [76]. Better CO_2 removal rate and biomass concentration of porous centric-tube indicate that this PBR provides a better mixing efficiency and higher photosynthetic rate due to perforation along the PBR [76]. Using membrane photobioreactors to enhance the CO_2 fixation rate of *C. vulgaris*, the CO_2 fixation rate of 6.6 $gl^{-1}d^{-1}$was achieved (Table 1) which was 0.95 times greater than those of conventional reactors [77]. Cheng et al., [78] used a photobioreactor with a hollow fiber membrane to remove CO_2 from air using *C.vulgaris* and enhanced the CO_2 removal rate from 1.92 to 6.24 g L^{-1} d^{-1} relative to non-membrane photobioreactors (Table 1). Membrane photobioreactors produce more uniform gas bubbles, increase bubble retention times around an order of magnitude, and decrease dissolved oxygen levels by a factor of thirty [77, 78].

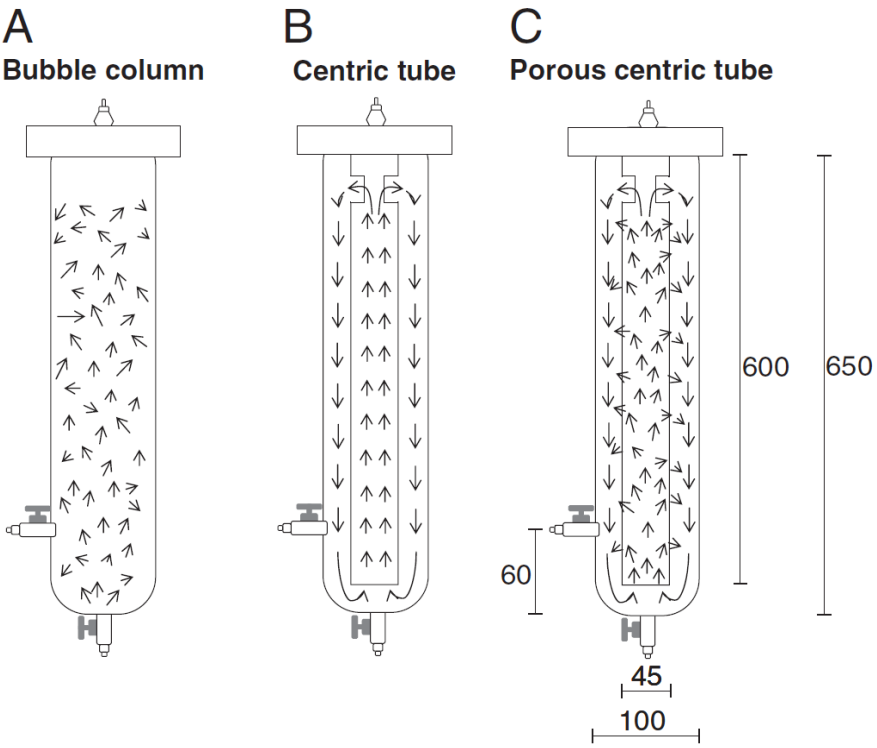

Fig. 1. Schematic diagram of three different types of photobioreactor and visualization of the liquid flow patterns. (A) Bubble column-type photobioreactor, (B) centric-tube photobioreactor, (C) porous centric-tube photobioreactor. (Unit of numbers is mm). (Reproduced from [76] with permission).

Table 1. Photobioreactor designs (PBR) and CO_2 removal rates.

Photobioreactor										**CO_2 fixation**		
Type	**Vol (L)**	**Microalgae**	**T (◦C)**	**Supplied CO_2 %**	**Flow gas rate (L min^{-1})**	**Growth rate (g d^{-1})**	**Cell density**	**Biomass concentration (g L^{-1})**	**Light intensity (Lux)**	**Rate (g L^{-1} d^{-1})**	**Efficiency (%)**	**Ref**
Bubble column (no inner column)	4	(1)	26	5	1	0.180	1 **g L^{-1}**	2.369	18750	-	24	[76]
Centric tube column	4	(1)	26	5	1	0.226	1 **g L^{-1}**	2.534	18750	-	23	[76]
Porous centric tube column	4	(1)	26	5	1	0.252	1 **g L^{-1}**	3.461	18750	-	35	[76]
Membrane PBR	-	(2)	25	(air & CO_2)	1.25	-	5×10^7 cell mL^{-1}	-	10800	6.6	-	[77]
Hollow fiber membrane	-	(2)	25-30	1	3	-	2×10^7 cell mL^{-1}	-	9800	6.24	70	[78]
Hollow fiber membrane	-	(2)	25-30	0.04	3	-	2×10^7 cell mL^{-1}	-	9800	-	67	[78]

(1) *Chlorella sp. NTCU2*- (2) *Chlorella vulgaris*

3. CO_2 concentration and CO_2 bioremediation using microalgae

Both the carbon source and microalgae strains are important when seeking to achieve high-productivity microalgae bioremediation of CO_2 from input gases. The most extended method to capture CO_2 from flue gases is absorption/desorption based on the utilization of alkanolamine solutions like monoethanolamine (MEA) or diethanolamine (DEA), etc. The CO_2 capture from flue gases using MEA/DEA absorption units requires a minimum of 4.0MJ kg^{-1} CO_2 for the regeneration of the solvent. The combustion heat of the microalgae biomass is around 20MJ kg^{-1} biomass and 1.8kg CO_2 are stoichiometrically required to produce 1kg of biomass, therefore, microalgae are able to accumulate 11.1MJ kg^{-1} CO_2 [79]. Thus, the capture of CO_2 represents a 36% (4.0 MJ kg^{-1}) CO_2 saving over 11.1 MJ kg^{-1} CO_2 (bioremediated) of the energy stored as biomass if the CO_2 was theoretically used at 100% efficiency. Experimental CO_2 removal rates were determined by Douskova et al., [80] who used flue gas (10-13% CO_2) and controlled gas (11% CO_2) to cultivate *Chlorella vulgaris*. The higher CO_2 fixation rate was achieved using flue gas (4.39g L^{-1} d^{-1}) in comparison with the controlled gas (3g L^{-1} d^{-1}). These results are likely due to other components of the flue gas (NO_x and SO_x) which increase microalgae biomass productivity [80]. Li et al., [81] used a mutant *Scenedesmus obliquus* WUST4 microalgae to capture CO_2 from flue gas and compared it with the original *S. obliquus* productivity when halving the CO_2 input gas concentration. The mutant strain accumulated a higher biomass concentration (0.922 g L^{-1}) than the non-mutant *S. obliquus* (0.653 g L^{-1}) even under 10% CO_2 concentrations compared with the non-mutant concentration of 20% CO_2. Furthermore, Chiu et al., [3] determined the growth curves of *Chlorella sp.* (wild-type, WT) and *Chlorella sp.* MTF-7 mutant aerated with flue gas or CO_2-enriched gas (2%, 10%, or 25% CO_2 aeration), finding the *Chlorella sp.* MTF-7 was significantly greater when aerated with flue gas or CO_2 (Fig. 2).

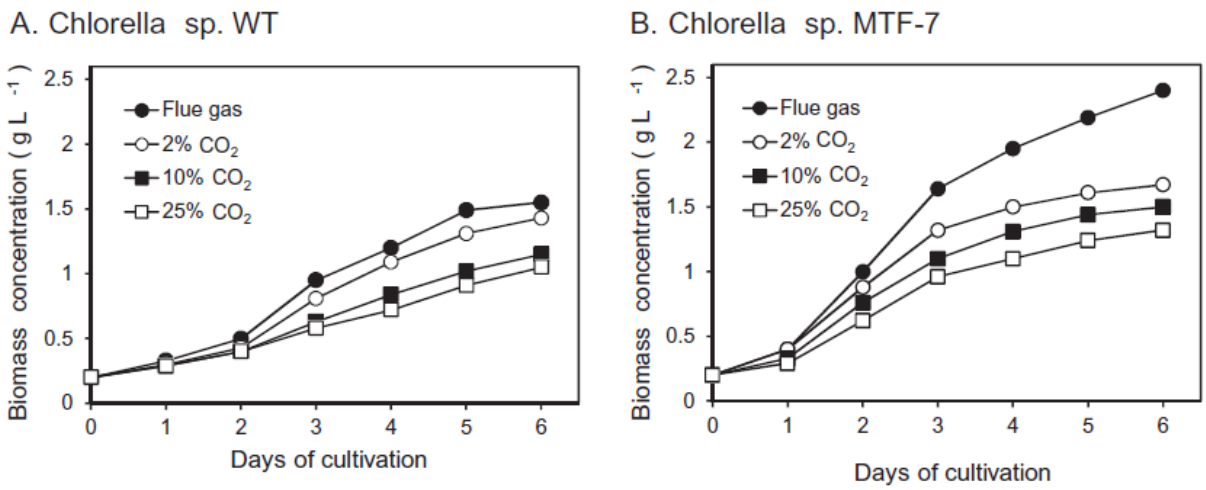

Fig. 2. Growth profiles of *Chlorella sp.* (wild-type, WT) (A) and its mutant, *Chlorella sp.* MTF-7 (B), cultured in an indoor photo-bioreactor aerated with continuous flue gas or CO_2-enriched gas (2 %, 10 %, or 25 %). The initial biomass concentration was approximately 0.2 g L^{-1}. The microalgal cells were cultivated at 300 µmol m^{-2} s^{-1}. The flue gas was provided at 0.05 vvm (volume of gas per volume of culture media per minutes). The cultures were grown for 6 days, and the microalgal cells were sampled every 24 h for growth determination.(Reproduced from [3] with permission).

Most research on bioremediation of CO_2 have been performed at the laboratory scale, and pilot scale experimentation is necessary to evaluate net CO_2 bioremediation on a continuous basis over an extended period. Research by Chen et al., [82] on *Spirulina platensis* cultivated in a 30m^3 photobioreactor utilizing CO_2 from a power plant was able to capture 2234kg CO_2 per annum. However, considering the cost and emissions of the required 130kWh of input electrical energy (1494 kg CO_2 per year), a net bioremediation of only 740kg CO_2 per annum was achieved [82]. Significant improvements of net CO_2 fixation rates ranging from 16.85g L^{-1} d^{-1} for *S. obliquus* to 40.32g L^{-1} d^{-1} for cyanobacterium *Aphanothece microscopica N¨ageli* was obtained by Francisco et al., [83], who investigated five microalgae species; *S. obliquus, Dunaliella tertiolecta, C. vulgaris, Phormidium sp., and A. microscopica N¨ageli* under 15% CO_2. The research found that the CO_2 fixation rates did not correspond exclusively to the biological assimilation of CO_2, and also that *A. microscopica N¨ageli* which achieved the highest CO_2 fixation rate also released toxic components into the medium that influenced the final use of the biomass.

3.1. High CO_2 tolerant microalgae species

The limiting factor of CO_2 fixation by microalgae is generally CO_2 mass transfer [44], and in general increasing CO_2 concentrations also leads to mass transfer enhancements. However, providing high levels of CO_2 into culture mediums leads to acidification, whereas consumption of CO_2 by microalgae through photosynthesis results in pH increase, and resultant changes may impact growth rates of some microalgae species [44]. When CO_2 is dissolved in an aqueous solution with a pH <8 the main pathway is direct hydration (at 25 °C and 1 atm), while at a pH >10 the main pathway is by the attack of hydroxide ions, and at pH between 6 and 10 bicarbonate is the dominant carbonate species [75, 79]. The hydroxide ions are transported to outside the cell by the enzyme carbonic anhydrase during photosynthesis. The other mechanism of pH increase is due to activity of the enzyme ribulose 1,5-bisphosphate carboxylase whose activity considerably depends on pH, increasing at higher pH levels [83]. Therefore, supplying high CO_2 to the culture medium should be matched with the optimum pH growth of the microalgae.

Fig. 3a and 3b shows the growth curve of *Scenedesmus* and *Chlorella* under high CO_2 concentration (10-80% CO_2) with *Scenedesmus* tolerating very high CO_2 concentrations to a greater extent than *Chlorella*, despite comparable growth rates of both microalgae in lower CO_2 concentrations of 10-30%. Fig. 4 indicates that the growth rate of *Scenedesmus* was inhibited under 100% CO_2 concentration, yet continued to grow when CO_2 concentrations returned to 20% [7]. Similarly, *Chlorella KR-1* was grown under elevated CO_2 ranging from air levels to 70 % CO_2, and Fig. 5 shows that the highest biomass concentration of 3.01g L^{-1} at a 10 % CO_2 concentration, and only 0.71 g L^{-1} under 70% CO_2 conditions [84]. Similarly, Tang et al., [85] assessed two microalgae strains, *S. obliquus SJTU-3* and *C. pyrenoidosa SJTU-2* at 50% CO_2 and determined the maximum biomass concentration of *S.obliquus SJTU-3* and *C. C. pyrenoidosa SJTU-2* was 0.82g L^{-1} and 0.69g L^{-1}, respectively.

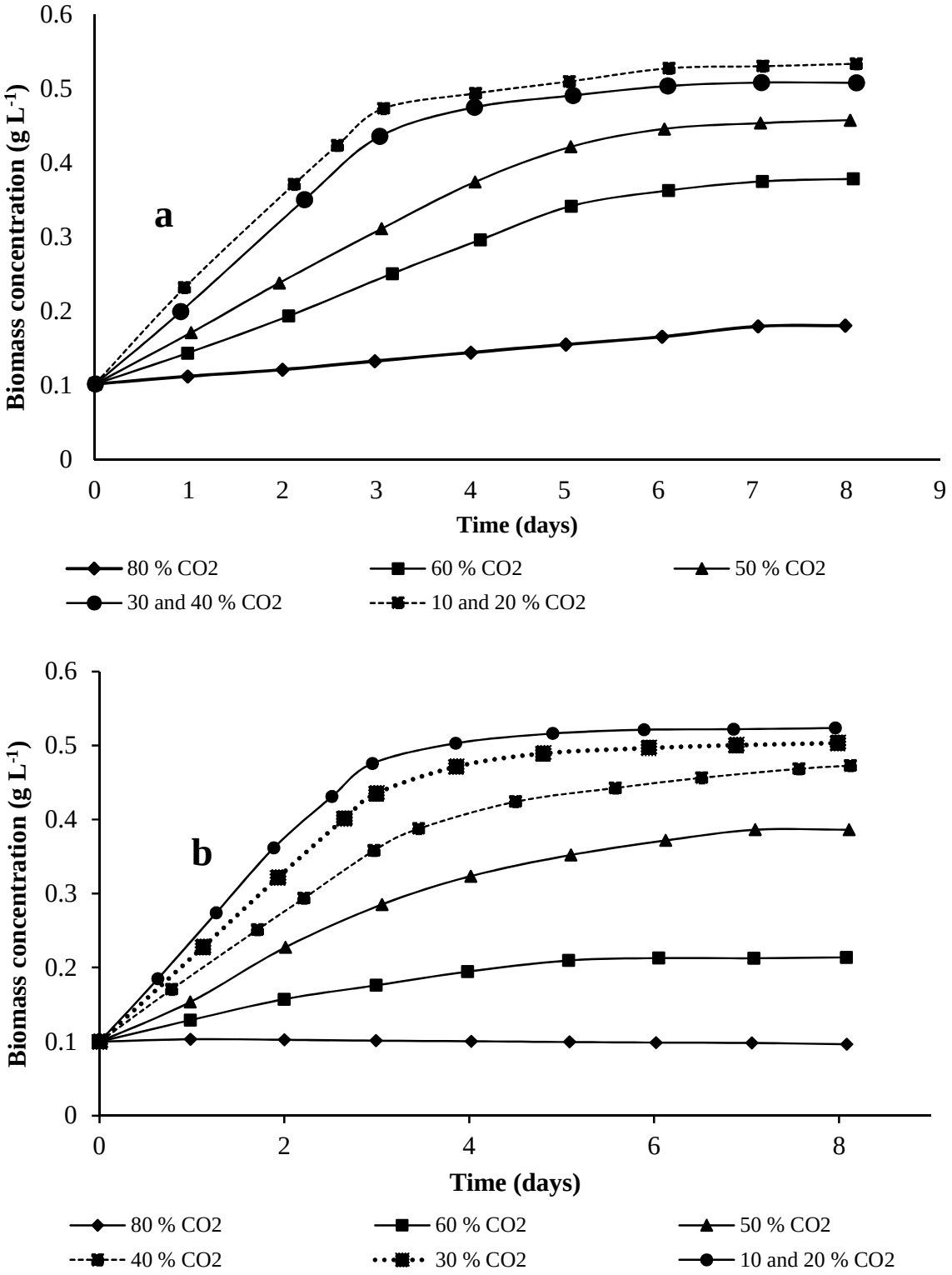

Fig. 3. Effect of different input concentrations of CO_2 on algal growth of (a) *Scenedesmus*, and (b) *Chlorella.* The cultures were grown at 30 °C and a light intensity of 60 $\mu Em^{-2}s^{-1}$. (Reproduced from [7] with permission).

Supplying high CO_2 concentrations with low gas flow rate leads to a low inorganic carbon loading in the liquid phase and a low concentration of DIC. Therefore, microalgae can tolerate high CO_2 concentrations with low gas flow rate. Using this method Olaizola et al., [86] was able to grow microalgae under 100% CO_2, and concluded that acidification was the main inhibitor of microalgal growth. In contrast, Soletto et al., [87] suggested that osmotic pressure is the primary source of growth inhibition. Clearly additional research is required for microalgae cultivation under high CO_2 concentrations, as other research has found growth also depends on cell densities [88], nutrients and light [75], and also on the species [7, 85].

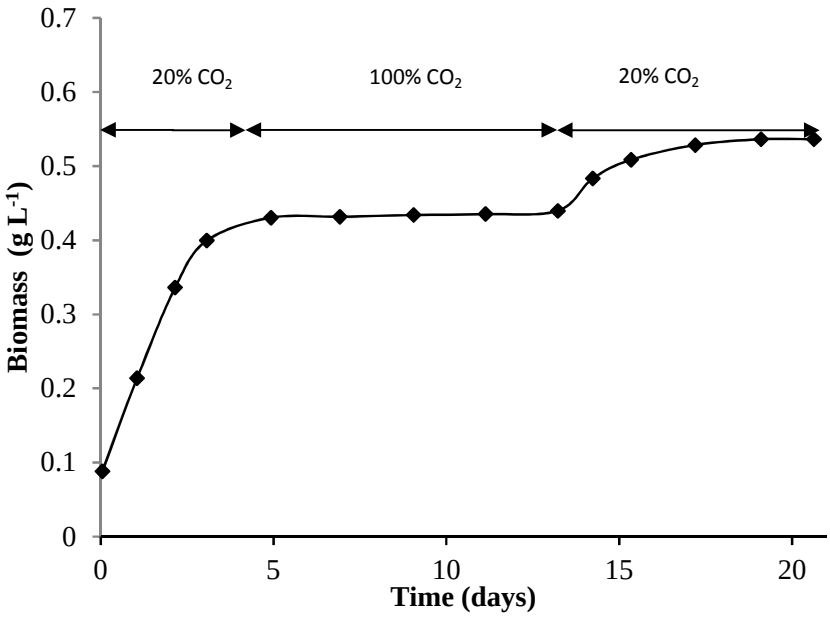

Fig. 4. The effect of bubbling culture medium under different CO_2 concentration on the growth rate of *Scenedesmus*. The experiment was carried out at 30°C and a light intensity of 60 $\mu Em^{-2}sec^{-1}$. (Reproduced from [7] with permission).

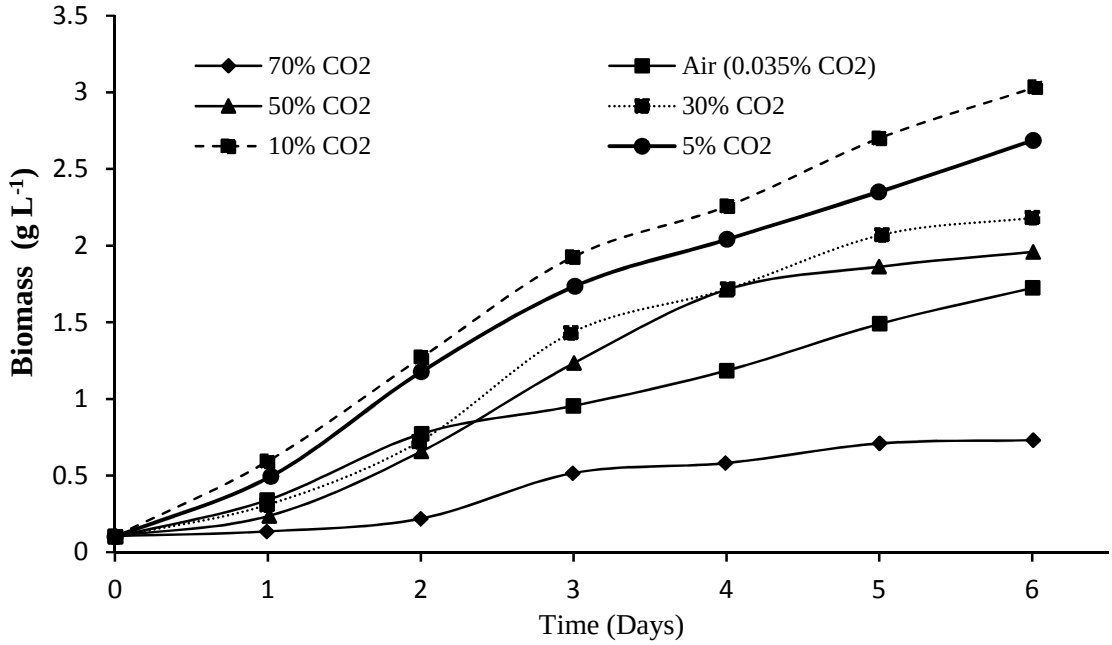

Fig. 5. Growth of *Chlorella KR-1*at different input concentrations of CO_2. The cultures were grown at 25°C and a light intensity of 110 µmol/m^2 sec, pH of the medium was 4.1 at an initial stage. (Reproduced from [84] with permission).

4. Temperature and CO_2 bioremediation

Temperature is another major factor in microalgal growth, particularly cell morphology and physiology, with metabolic rates generally rising and falling with changing temperatures. However, CO_2 solubility decreases in higher culture temperatures leading to lower CO_2 availability. CO_2 solubility also depends on culture pH, decreases with increasing salt concentration, and increases with higher pressures. Thus, to generally improve the solubility of CO_2 the culture medium must be maintained at a cooler temperature [89], yet each microalgae species has its own optimal-growth temperature, and is generally within the range of 15-26 °C [20]. The use of thermo-tolerant microalgae species for CO_2 removal from hot flue gases is a major advantage in reducing production system cooling demands. Thermo-tolerant microalgae species have the ability to grow at temperatures up to 55 °C in more than 40% CO_2 input gas concentrations, making them highly prospective for CO_2 bioremediation from power station flue gases [2]. *Cyanidiwn caldarim, Galdieria partita* and *Cyanidioschyzonmelorae* exhibit acceptable growth rates

at 50 ºC [90], and *Thermo synechococcus elongatus* (a unicellular cyanobacterium) grows in hot springs at temperatures of 48-55 ºC [91]. Two thermal-tolerant mutants of *Chlorella sp. MT-7* and *MT-15* were investigated in indoor cultivation by Ong et al., [92]. The specific growth rate of the mutants were 1.4 to 1.8 times at 25ºC and 3.3 to 6.7 times at 40ºC higher than those of the wild type, with the mutant strains maximum growth rates at 30ºC. Table 2 also shows that mutant strains analysed exhibited significantly higher CO_2 fixation rates than wild types at higher temperatures [92]. Hsueh et al., [23] examined two strains of *Thermo synechococcus sp. CL-1 (TCL-1)* and *Nannochloropsis sp. oculta (NAO)*. For NAO, the maximum growth rate of about 1.6g d^{-1} and biomass concentration of 1.41g L^{-1} was obtained at 30°C under 8% CO_2 [23]. As shown in Fig. 6a, the growth rate and maximum cell mass of NAO is practically the same at 30ºC and 40ºC at ~0.4g L^{-1}. The *TCL-1* strain growth rate and the maximum cell mass both increased as the temperature rose from 40 to 55ºC (Fig. 6b). For *TCL-1*, at 40, 50, and 55ºC, the CO_2 uptake rate was 0.069, 0.141 (Table 2) and 0.237g L^{-1} d^{-1}, respectively [23]. Ono et al., [93] used *Chlorogleopsis sp.* (or SC2), a thermophile cyanobacterial species and found the maximum carbon uptake and cell concentration were 0.204g L^{-1} d^{-1} and 1.24g L^{-1}, respectively at 5% CO_2 level at 50ºC.

In general at higher temperatures the available CO_2 decreases because of lower solubility in the microalgal culture. At 30°C Henry's Law constant of CO_2 in water is 2.965×10^{-2} mol/atm, while it declines to 1.817×10^{-2} mol/atm at 50ºC [91], leading to higher CO_2 availability and generally higher microalgae CO_2 uptake [91]. This is balanced with the increasing metabolic rates at increasing temperatures. Detailed investigations of the dynamics two mechanisms together are yet to be explored fully in the available published literature.

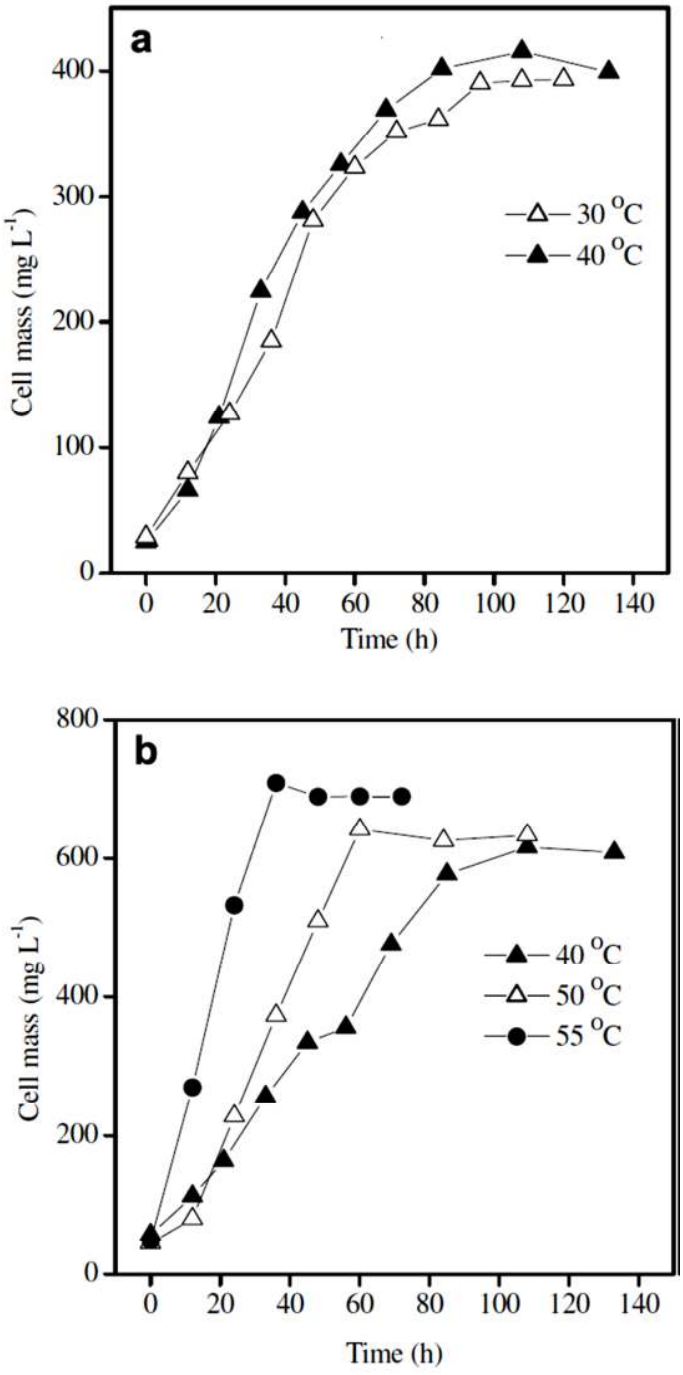

Fig. 6. Growth curves at different temperatures. (a) NAO at pH 8.5. (b) TCL-1 at pH 9.5. (Light intensity: 10 k lx). (Reproduced from [23] with permission).

Table 2. CO_2 removal rate of microalgae species at high temperatures.

Photobioreactor										CO_2 fixation		
Type	**Vol (L)**	**Microalgae**	**Temp (◦C)**	**Supplied CO_2%**	**Flow gas rate (L min^{-1})**	**Growth rate (d^{-1})**	**Cell density (g L^{-1})**	**Biomass concentration (g L^{-1})**	**Light intensity (Lux)**	**Rate (g L^{-1} d^{-1})**	**Efficiency (%)**	**Ref**
Vertical bubble column	40	3	40	5	20	-	2	-	1500	0.019	-	[92]
Vertical bubble column	40	4	40	5	20	-	2	-	1500	0.021	-	[92]
Bubble column	-	5	30	8	1	1.6	-	1.41	10000	-	-	[23]
Bubble column	-	6	50	10	-	2.7	-	-	10000	0.141	-	[23]
-	-	7	50	5	0.002vvm	0.28	-	1.24	12500	0.204	-	[97]

(3) *Chlorella sp MT-7 - (4) Chlorella sp MT-15 - (5) Nannochloropsis sp. Octula (NAO) - (6) Thermosynechococcus sp. CL-1 (TCL-1) – (7) Chlorogleopsis sp (SC2)*

5. Lighting and CO_2 bioremediation rates

Light intensity controls photosynthetic growth in any algal system. Light intensity affects photosynthesis, CO_2 removal rates, biomass concentrations, and overall growth rate. Research by Hulatt et al., [94] on CO_2 removal rates for both *C. vulgaris* and *D. tertiolecta* under 4% CO_2 with increasing light intensities (10, 20, and 50 W m^{-3} presented in Table 3 shows *C. vulgaris* and *D. tertiolecta* were 0.72, 0.83, 0.93g L^{-1} and 0.9, 1.18, 1.31g L^{-1}, respectively. Similar results were achieved in research by Takano et al., [95] found the CO_2 fixation rate of the cyanobacterium *Synechococcus sp.* rose from 0.1 g L^{-1} to 0.4 g L^{-1}, and a 4.2 times biomass yield was observed by increasing the light intensity from 156 to 1250 lux (Fig. 7). While increasing light intensity is usually accompanied by increasing CO_2 removal rates in microalgal systems, any photosynthetic system has a saturation point where further increasing light intensity will either produce no benefit or may decrease productivity. As shown in Fig. 8, CO_2 fixation and O_2 evolution rates have a positive correlation with light intensity until the saturation point at 10800 lux [77]. Investigation by Li et al., [81] on *S. obliquus WUST4* showed that with increasing light intensity from 6000 lux to 15000 lux, CO_2 removal rates increased with the highest CO_2 removal ratio (67%) at 12000-13000 lux. However, as the light intensity exceeded 13000 lux, the CO_2 removal ratio decreased at high light intensities as microalgal photosynthesis was inhibited [81]. The characteristics of light can also play a significant role in CO_2 fixation. The variable effects of sunlight, xenon lamps, and fluorescent lamps on CO_2 fixation rates of *Chlorella sp* was investigated by Hirata et al., [96]. The research found that cultivation under white fluorescent lamps achieved the highest CO_2 fixation rate (0.865g L^{-1} d^{-1}), biomass concentration (0.842g L^{-1}) and biomass productivity (0.437g L^{-1} d^{-1}) [96]. (See Table 3).

[Insert Table 3 and Fig 7 8]

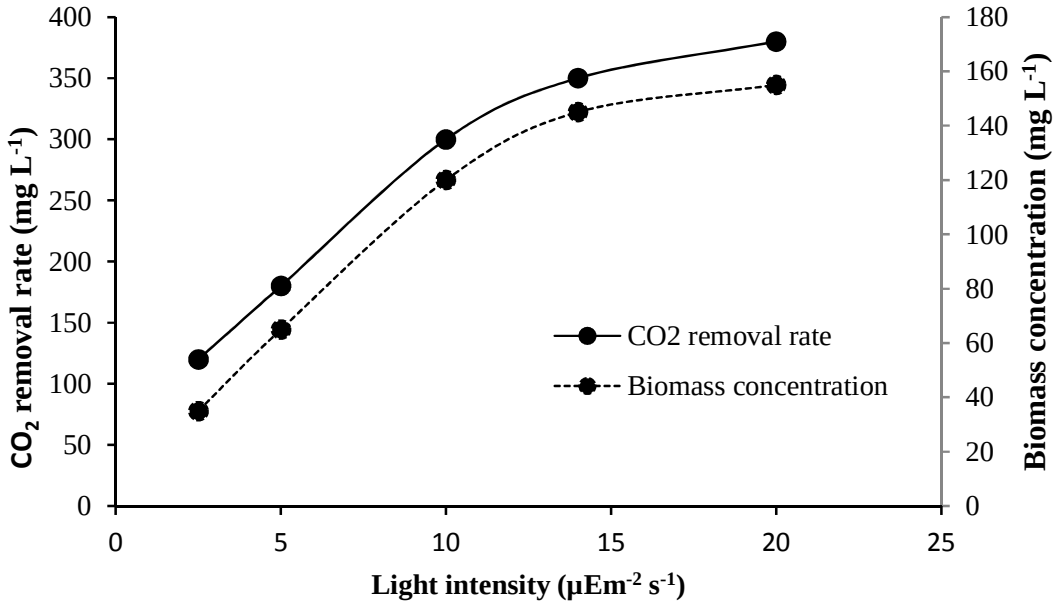

Fig. 7. Effect of light intensity on CO_2 removal and biomass concentration. (Reproduced from [95] with permission).

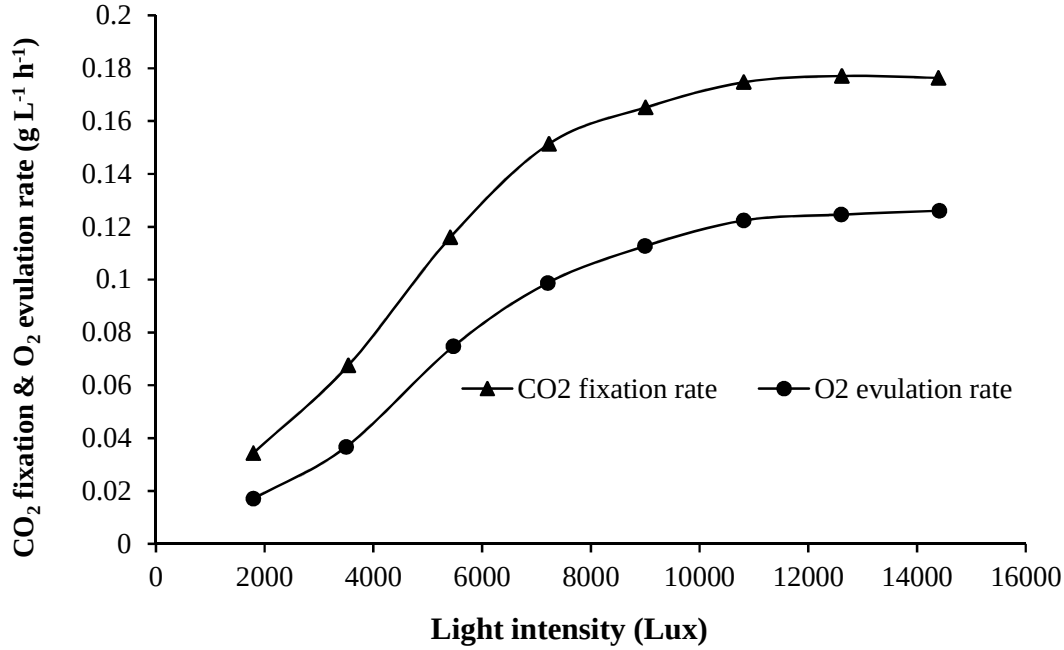

Fig. 8. Effect of luminous intensity on CO_2 fixation and O_2 evolution of *Chlorella vulgaris*, (T = 25 °C, cell number = 5 · 107 cells mL^{-1}, gas flow rate = 1.25 L min^{-1}, red inner light source, PVDF-1membrane length = 30 cm and membrane number = 30). (Reproduced from [77] with permission).

Table 3. Effect of photobioreactor (PBR) light intensity on CO_2 fixation rates.

Photobioreactor		Microalgae	Temp (◦C)	Supplied CO_2 (%)	Flow gas rate (L min^{-1}	Cell density (g L^{-1})	Biomass concentration (g L^{-1})	Biomass productivity (g L^{-1} d^{-1})	Light intensity (W m^{-3})	CO_2 fixation		Ref
Type	Vol (L)									Rate (g L^{-1} d^{-1}	Efficiency (%)	
Bubble column	1.4	2	26	4	0.001 ms^{-1}	-	2.7	0.41	10	0.72	14.6	[94]
Bubble column	1.4	2	26	4	0.002 ms^{-1}	-	3.18	0.42	20	0.83	8.5	[94]
Bubble column	1.4	2	26	4	0.005 ms^{-1}	-	3.62	0.47	50	0.93	3.8	[94]
Bubble column	1.4	8	26	4	0.001 ms^{-1}	-	3.03	0.51	10	0.9	18.4	[94]
Bubble column	1.4	8	26	4	0.005 ms^{-1}	-	3.33	0.66	20	1.18	12	[94]
Bubble column	1.4	8	26	4	0.005 ms^{-1}	-	3.60	0.73	50	1.31	5.3	[94]
PBR	-	9	30	10	0.5	16	0.150	0.016	Sunlight (0-15.7)	0.031	-	[90]
Roux flask	-	9	30	10	0.5	16	0.694	0.368	Xenon lamp (59.9)	0.728	-	[90]
Roux flask	-	9	30	10	0.5	16	0.842	0.437	Florescent lamp (71.4)	0.865	-	[90]

(2) *Chlorella vulgaris – (8) Dunaliella tertioleeta – (9) Chlorella sp*

6. Conclusions

CO_2 bioremediation by microalgae depends on photobioreactor geometry and mass flow, input CO_2 concentrations, cell concentrations, the light intensity and temperatures. Results presented in this review article demonstrated that the type of photobioreactor impacts the efficiency of CO_2 bioremediation. Microalgae start the transport of electron reactions in the presence of light. The results showed that while increasing light intensity normally leads to CO_2 removal enhancement by microalgae, further research is required to determine optimal light characteristics and intensities suited to each alga and culture system. Similarly, maintaining culture growth temperatures (normally 23-30 ^oC) influence CO_2 fixation, particularly when employing exhaust flue gases is a promising strategy, yet requires local customization to each unique flue gas temperature and chemistry – particularly trace elements that can kill the microalgae. Using microalgae for CO_2 bioremediation is more beneficial over chemical methods. Being environmentally friendly, saving ecosystem sustainability and producing useful products makes these species attractive. Furthermore, employing wastewater as nutrient and flue gas, containing 15-20 % CO_2, as feed gas for microalgae is a promising strategy to produce sustainable energy such as biodiesel and biofuel while reducing pollutant from the environment.

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