Short Perspective on Membrane Integration in Microalgae Bioreactor for CO_2 Capture

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Abstract. The global warming issue has reached an alarming level due to the continuous increase of CO2 and other greenhouse gas emissions. They are released into the atmosphere due to anthropogenic activities and contributions from many industries that employ coal, fuel oil, and natural gas. To achieve environmentally friendly and sustainable conditions, CO2 capture is important. This article starts by discussing the comparison of several methods in CO2 capture, continues with the performance of CO2 capture in microalgae bioreactor (photo-bioreactor), and closed with the prospect of membrane integration in photo-bioreactor. There are physical, chemical, and biological methods for capturing CO2. Physical method leads to expensive processes and chemical method leads to producing chemical waste. Biological method using microalgae is considered attractive and several factors affected the capture process, i.e. temperature, pH, light intensity, microalgae strain, types of bioreactor, CO2 and toxic substances concentration (SO2 and NOx), and illumination cycle. This article discloses that airlift and flat panel photo-bioreactors are promising for CO2 capture because of their high volumetric productivity, high photosynthetic efficiency, high gas transfer, and uniform mixing. Furthermore, membrane integration in photo-bioreactors increases the capture efficiency as it can produce fine bubbles for better CO2 mass transfer into the medium. Therefore, microalgae cultivation combine with membrane process has a potential prospect for environmental remediation while producing valuable products from microalgae.

Keywords: CO_2 capture · Global warming · Membrane · Microalgae · Photo-bioreactor

1 Introduction

The CO2 emissions have led to global warming and climate change [1–6]. As much as 87% of all human-produced CO2 emissions derive from coal (43%), natural gas (36%), and fuel oil (27%). The other is from oceans, soils, plants, animals, volcanoes, and biodegradation of organic wastes [1]. Normally, flue gas from industrial areas contains 10–15% of CO2. Meanwhile, CO2 concentration in the air is only 300–600 ppm, with an average of 400 ppm [7]. Consequently, CO2 in the flue gas should be processed before

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Table 1. The maximum concentration of CO_2 and SO_2 emission from different [7–10]

Specifications	CO_2 (%)	SO_2 (ppm)
Natural gas	11.8–11.9	200–1000
Propane	13.8	–
Butane	14.1	–
Fuel oil	15.4–16.5	14000–16000
Coal	11.8–19.2	340–400
Coke	20.1–20.6	–
Liquid gas	13.9	–
Waste incinerator	6–12	200–1500
Town gas (metropolitan)	11.6–13.0	100–500
Coal industries	11.8–12.4	399.3–450.5

releasing it into the atmosphere. Table 1 shows the maximum concentration of CO2 and SO2 from several sources.

The potential and attractive route for capturing it is using microalgae. Generally, 1 kg of microalgae can utilize 1.83 kg CO_2 from flue gas [11]. Microalgae are photosynthetic microorganisms that utilize CO2 as their carbon source [12]. Microalgae are widely applied in aquaculture, pharmaceutical, energy, and environment sectors. In the aquaculture sector, microalgae are often applied as live feed for fish, shrimp, zooplankton, rotifers, and artemia. In the pharmaceutical sector, microalgae from Spirulina is used as health supplements and cosmetics due to its high protein [13].

Besides, microalgae have been recognized as a promising alternative raw material for biofuel production. Nevertheless, uneconomical and inefficient methods in large-scale cultivation and harvesting become a major drawback [14–16]. Mostly, existing microalgae production uses centrifugation for harvesting which is energy-intensive because occupies a major fraction of the total production energy demand [17]. Another challenge is the low concentration of microalgae in the culture medium of only 0.5–2 g/L [15]. Interestingly, membrane integration in the bioreactor to cultivate microalgae has the potential to overcome those problems [18]. According to the aforementioned description, it is then interesting to discuss the carbon capture technology using microalgae. This article starts with comparison of several methods in CO_2 capture, performance of CO_2 capture in photo-bioreactor, and prospect of membrane integration in photo-bioreactor.

2 Methods

There are several methods for capturing CO_2 such as chemical, physical, biological, physicochemical, and combination of each other. Their advantages and disadvantages are outlined in Table 2. In chemical method, CO_2 is captured by wet scrubber technology with water or amine-based solvent. Lime is usually added to augment the CO_2 solubility in water and the solvent should be regenerated to reduce the operational cost. The treatment of chemicals also becomes a major concern because they cannot easily dispose of in the environment. They should be neutralized and the cost is relatively high. In physical method, activated carbon is the common treatment for flue gas. The capturing efficiency can be up to 95%, but the process is somewhat expensive. Cryogenic technology can also capture CO_2 but require a tremendous-cost process and need a high mechanical strength of materials [19].

Other than that, there are many methods in biological treatment for CO_2 capture such as bio-trickling filter, bio-filtration, bio-scrubber, bioreactor, and raceway pond. In attached growth bioreactor or bio-trickling filter, microalgae are grown only on the surface of the attached media (e.g. sand, rock, and bed) forming flocs and are then

Table 2. Comparison of several methods in CO_2 capture

Methods		Advantages	Disadvantages	Capturing Efficiency (%)	References
Chemical	Chemical absorption (wet scrubber)	High performance	Need high energy for recovering CO_2	60–95	Palmeri et al., 2008; Wang et al., 2004; Yang et al., 2008; Goli et al., 2016
Propane	Chemical packed bed scrubber				
Physical	Physical adsorption (active carbon)	Easy to operate and no need chemical	Need high energy when recycling adsorbent	55–92	Yang et al., 2008; Rege et al., 2000; Wang and Lee, 2009
Fuel oil	Filtration		Cake deposition		14000–16000
Coal	Cryogenic	Very high performance	Very expensive	>99	Hart and Gnanendran, 2009; White et al., 2009; and Goli et al., 2016
Biological	Photo-bioreactor	High doubling time	Contamination may occur	90–95	Powell and Qiao, 2006; Goli et al., 2016
Liquid gas	Raceway pond				
Physicochemical	Membrane bioreactor	Flexible, and easy to operate and scale up in multi-stage	Low selectivity at higher permeability	50–90	Merel et al., 2006; Paranjape et al., 1998; Stewart and Hessami, 2005; Powell and Qiao, 2006
Combination		Very high performance	High cost	>90	Rege et al., 2000; Powell and Qiao, 2006; Goli et al., 2016
Chemical	Chemical absorption (wet scrubber)	High performance	Need high energy for recovering CO_2	60–95	Palmeri et al., 2008; Wang et al., 2004; Yang et al., 2008; Goli et al., 2016

aggregated to biofilm. The transport process involved is the transference of CO_2 into the liquid phase (external diffusion), adsorption into the microalgae biofilm (internal diffusion), and usage of the CO_2 by microalgae biofilm. Meanwhile, bio-scrubber is well-known as an effective and efficient gas phase treatment, but it is expensive and can produce chemical wastes. The photo-bioreactor is a highly efficient biological method for treating flue gas. The CO_2 fixation process consists of the following phase: the transference of CO_2 into the aqueous phase (external diffusion), diffusion of CO_2 into the cell (internal diffusion), and CO_2 fixation within the cell which is used for its growth.

Compare to terrestrial C_3 plants, microalgae are more productive in CO_2 capture**.** Other advantages of using microalgae are given in Table 3. The CO_2 capture using microalgae has a potency for producing many valuable products such as bioethanol, food & feed, biopolymer, bio-fertilizer, biogas, and biodiesel. Bioethanol is produced from microalgae cultivation and can be refined to fuel-grade ethanol. Industries are prohibited to co-fire microalgae with coal because it contains proteins that produce NO_x [20]. Meanwhile, the co-processing of dilute microalgae with wastewater treatment plants (WWTP) or chemical waste adsorption is promising.

The concentrated microalgae can be used to produce food & feed employing single-cell proteins, biopolymer, and bio-fertilizer. Concentrated microalgae are also applied as a substrate for producing raw biogas by anaerobic digestion. Subsequently, the raw biogas is then sweetened to form bio-methane and then CO_2 is recycled back as a microalgae carbon source. Additionally, the high-contained saturated and unsaturated lipids in microalgae are suitable for biodiesel feedstock. The routes for microalgae utilization are depicted in Fig. 1.

Table 3. Advantages of microalgae over terrestrial C_3 plant

Factors	Microalgae	Terrestrial C_3 Plant	References
Response to Climatic Change	Fast	Slow	Mata et al., 2010 [21]
Competition to agricultural food production	No	Yes	Radakovits et al., 2009 [22]
Photon conversion efficiency	8–10%	0.5%	Aresta et al., 2005; Sharma et al., 2011 [23, 24]
CO_2 Bio-fixation Efficiency	High	Low	Kumar et al., 2011 [25]
Growth rate	Rapid	Slow	Greenwell et al., 2010; Mata et al., 2010 [14, 21]
Production and Harvesting	Annual	Seasonal	Kumar et al., 2011 [25]
Scale up	Easier	Complex	Clarens et al., 2010 [26]
Cultivation costs	Low	High	Kumar et al., 2011 [25]

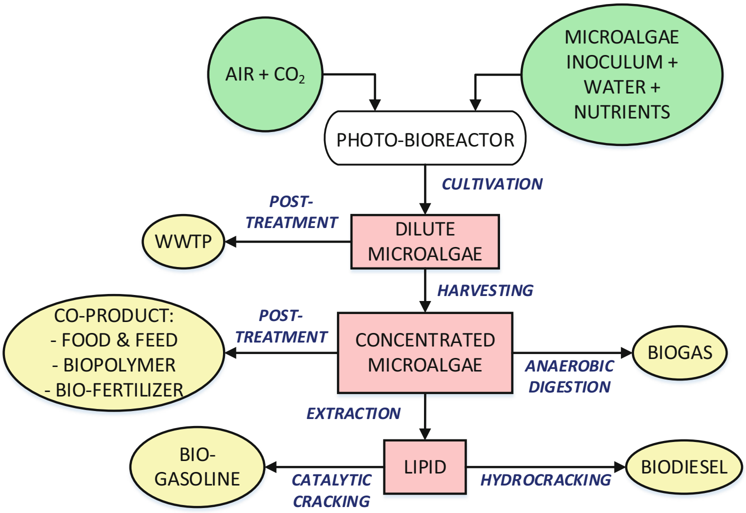

Fig. 1. Routes of microalgae utilization

3 Results and Discussion

3.1 Factors Affecting CO2 Capture Performance in Photo-bioreactor

Many factors affect CO2 capture using photo-bioreactor, such as microalgae strain, types of photo-bioreactors, nutrition concentration in the medium, CO2 concentration, temperature, pH, light, and the presence of toxic gas. In a multi-step process of photosynthesis, microalgae fix CO2 in the atmosphere using light and convert it to biomass cells and biomolecular products (lipids, amino acids, carbohydrates, and other metabolites).

Photo-bioreactor

Two major techniques in cultivating microalgae are open ponding and closed system. The principle is to achieve a high surface area per volume to provide more surface area for light penetration and CO2 transfer. Open ponding is the most commonly applied for large-scale microalgae cultivation due to its low cost and ease of operation and maintenance. However, requiring large areas, high risk of contamination, evaporative water loss phenomenon, and difficulty to control become disadvantages. Closed system cultivation has been studied due to the ease of regulating microalgae growth and can achieve high photosynthetic efficiency as well as biomass production compared to open ponding. It is widely used for pharmaceutical purposes or highly selective products application. In airlift photo-bioreactor, the liquid volume is separated into two connected zones by baffles. It gave the most fixation efficiency due to its relatively better mass transfer and circulation.

The diverse types of photo-bioreactor have affected the productivity of biomass production and the efficiency of CO2 capture. There is a raceway pond where microalgae were grown in a pond that looks like a race track equipped with paddle wheel agitation.

It is the most commonly used for large-scale microalgae cultivation due to its cost-effectiveness. These ponds are designed in such a way that two trenches are dug in the ground, forming a rectangular raceway, and the water flows in a circular motion around the pond like a race track.

Stirred tank photo-bioreactor is a conventional bioreactor that is equipped with mechanical agitation with different shapes and sizes of the impeller. The baffle is usually used to avoid vortex. Air containing CO2 is sparged from the bottom of the reactor. Its disadvantages are high shear stress and low surface area to volume ratio so it decreases CO2 capture efficiency. The illumination uses a fluorescent lamp or optic fiber, but optic fiber has some disadvantages because of its hindrance in mixing patterns.

Vertical tubular photo-bioreactor is a vertical tubing reactor made of transparent material to allow light penetration. The diffuser is attached below the reactor. This bioreactor is divided into bubble column and airlift types. The biomass productivity of microalgae cultivated in a column airlift photo-bioreactor was 15–36% higher than in a conventional one due to a more uniform mixing [27]. On the other hand, horizontal tubular photo-bioreactor is similar to vertical one and usually has an inclined area toward the sun and resulting in high volumetric productivity and high photosynthetic efficiency [28]. Other than that, helical type photo-bioreactor consists of coiled transparent and degassing unit. A centrifugal pump is used to flow the culture along the tube, but fouling inside the reactor may happen.

Flat panel photo-bioreactor has a cuboidal shape with a minimal light path. The material is also transparent and has a high surface area-to-volume ratio. Aeration is facilitated by bubbling from one side of the reactor. Usually, the transparent cooling jacket was installed on the front illuminated side to control the temperature of the culture broth. Microalgae productivity is 1.7 higher than tubular photo-bioreactor [29]. Bag photo-bioreactor is widely used for lab-scale microalgae semi-continuous production.

There is also an integration of membrane into the airlift or tubular photo-bioreactor to produce fine bubbles for better CO2 mass transfer into the medium. This is usually called membrane photo-bioreactor which has advantages comprising easy to install, high CO2 distribution, and prevent O2 build-up. The membrane should have resistant to alkaline and acidic conditions and have low fouling potential. Also, low porosity of membrane generates microbubbles which provide better CO2 mass transfer, resulting in a higher CO2 fixation rate. The advantages and disadvantages of several bioreactors are described in Table 4.

Microalgae Strain and Cell Density

For better cultivation performance, the microalgae strain should have high sinking capacity and high tolerance to hydrodynamic stress and toxic substances. Productivity and light utilization efficiency are the functions of cell density. Thus, it is very important to select the optimum cell density in order to achieve a high CO2 capture efficiency. Below the optimum cell density, not all the light is utilized. Above the optimum cell density, each cell does not get sufficient light due to self-shading. However, high cell density makes microalgae more tolerant to high CO2 concentrations.

Nutrients and Toxic Substances

Carbon, nitrogen, and phosphor are the three essential nutrients for microalgae growth.

Table 4. Comparison of different photo-bioreactors

Photo-bioreactor Types	Advantages	Disadvantages	References
Bubble Column	High CO_2 fixation efficiency and biomass productivity; Simple to operate and easy to control nutrients, light, and CO_2 concentration; Low cooling requirement; Zero waste process; Almost all pollutants capable of removed; Effective light use	Expensive for large cultivation and production; High pressure drop; High costs; Problem was found in treating acidic gas	Sen, 2012; Fulazzaky et al., 2014; Carvalho and Malcata, 2001; Klinthong et al., 2015
Vertical Tubular	Compact; High mass transfer; Good mixing; Low energy consumption; Easy to scale up and sterilized; Recommended for immobilized microalgae growth; Low photo-inhibition and photo-oxidation; Excellent temperature control	Small illumination surface area; difficult to construct; expensive compared to open ponding; Tend to foul	Powell and Qiao, 2006; Merel et al., 2006; Goli et al., 2016; Klinthong et al., 2015
Flat Panel	Broad illumination surface area; Suitable for outdoor microalgae cultivation; Excellent temperature control; Recommended for immobilized microalgae growth; High CO_2 fixation rate; Low-cost operation; Easy to clean; Low oxygen build-up; Low cooling requirement; High gas transfer coefficient	Difficult to scale up and control the temperature; high hydrodynamic stress	Paranjape et al., 1998; Stewart and Hessami, 2005; Sen, 2012; Fulazzaky et al., 2014

(*continued*)

Table 4. (*continued*)

Photo-bioreactor Types	Advantages	Disadvantages	References
Airlift	Good light use; High-temperature control; High mass transfer coefficient; Low hydrodynamic stress	Difficult to scale up	Sen, 2012; Klinthong et al., 2015
Horizontal Tubular	Broad illumination surface area; Suitable for outdoor microalgae cultivation; Easy to scale up; High CO_2 fixation rate; Low-cost operation; Excellent temperature control	High pH gradient; fouling phenomenon; Require large land area	Brennan and Owende, 2010; Klinthong et al., 2015
Raceway Pond	Low investment; High efficiency; Zero waste process; Effective for large-scale microalgae cultivation and production; Require natural mass transfer mechanism	Require enormous land area; Difficult to operate and control cultivation conditions; Uncontrolled and unwanted other species growth occur; Limited CO_2 mass transfer; Low productivity; Reduced light intensity with increased depth	Paranjape et al., 1998; Stewart and Hessami, 2005; Powell and Qiao, 2006
Bio-trickling Filter	Low cost and simple operation; No inoculation needed; Almost all pollutants capable to removed	High-pressure drop; Plugging, drying, and channeling	Carvalho and Malcata, 2001 and Brennan and Owende, 2010
Bio-scrubber	No plugging, no drying, and no channeling	Expensive and complex operation; Produce wastewater	Sen, 2012; Fulazzaky et al., 2014
Suspended Growth	Easy to control biomass and nutrient; Zero waste process	High pressure drop; Plugging, drying, and channeling; Complex operation	Yen et al., 2014; Goli et al., 2016

Typically, Chlorella sp. And Scendesmus sp. Are the most notable microalgae in assimilating those nutrients in the wastewaters to produce high biomass yield. Also, there are some toxic substances for microalgae: SO2 and NOx. Both gases are sour and cultivating acidophilic microalgae can be a prospect. 150 ppm SO2 condition is the maximum concentration for microalgae cultivation. Microalgae can tolerate high concentration which is up to 300 ppm of NOx because NOx is not directly inhibiting its growth.

CO_2 Concentration, pH, and Temperature

Nannochloropsis sp. Strains were able to grow when SOx concentration was below 50 ppm. Also, NO2 and NO are typically found in industrial flue gas in the range of 5–10%v/v and 90–95%v/v. NO concentration of below 300 ppm did not show any negative effect on microalgae growth. NOx is used as a nutrient for microalgae during CO2 capture. For producing high lipid yield from microalgae, the nutrient must have less nitrogen source to inhibit the carbohydrates and proteins metabolism.

In an aqueous environment, dissolved CO2 always exist in the equilibrium of HCO3-, H2CO3, and CO32- which depends on pH and temperature. The optimal pH for microalgae growth ranges from 6.8–9.0. The pH of the culture medium is very influenced by dissolved CO2 and SO2 from the flue gas. Low pH will inhibit the CO2 capture process and medium supplemented with buffer solution can overcome this. The preadaptation of cells with a lower percentage of CO2 concentration leads to the tolerability of cells with a higher percentage of CO2. The excess CO2 increased photosynthetic activity and phototrophic biomass production but blocked the production of metabolites (Maeda et al., 1995). The growth rate of Nannochloropsis sp. Was increased by 58% under the cultivation of 15%v/v of CO2.

Zhao et al. (2015) [20] reported that capturing CO2 from flue gas using Nannochloropsis oculata in a glass photo-bioreactor had suitable operating conditions comprising an initial CO2 concentration of 2–15% and NOx/SO2 of 0.02. The CO2 fixation efficiency was between 11–55% and CO2 consumption rate was 564 mg/L/day. The yield was 300–490 mg/L/day and lipid productivity was 80–150 mg/L/day. The optimum pH in the raceway pond was observed to be up to 10.

The low temperature of the culture medium is unfavorable for the Rubisco activity, leading to a reduction in photosynthesis rate. In contrast, high temperature inhibits microalgae rate and reduces CO2 solubility. The optimal growth temperatures for mesophilic microalgae are 15–30 °C. However, thermophilic organisms are able to live at 45–122 °C. The flue gas is usually emitted at 120 °C, so installing heat exchanger or waste heat utilization becomes important.

Light Intensity and Illumination Cycle

Sunlight and artificial light are commonly employed in cultivation. The intensity depends on its wavelength, cell density, bioreactor geometry, and light penetration distance. The range of light wavelength for microalgae is 400–700 nm. Excessive light causes photoinhibition so it will decrease microalgae productivity and too low of light intensity will inhibit photosynthesis [30]. The light zone for suitable microalgae growth is depicted in Fig. 2.

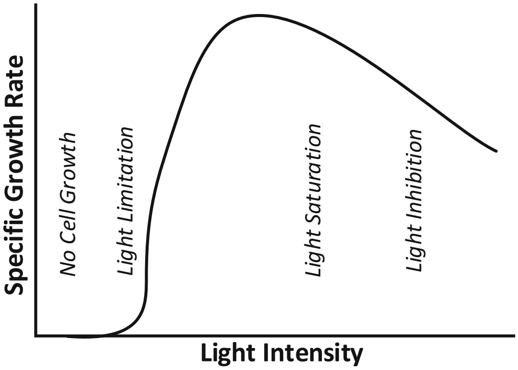

Fig. 2. Effect of light intensity on microalgae growth

Mixing and Aeration

CO2 has low solubility in the medium, so the mass transfer from gas to liquid phases is low. Mixing and aeration can be a solution to enhance the gas and liquid interface areas, homogenize nutrients, prevent photo-oxidation, improve the distribution of light over cells, control the pH, and strip off dissolved oxygen. Several mixing and aeration techniques in microalgae cultivation are mechanical stirrings, gas injection through bubble diffusers, and membrane-sparged devices (only for membrane photo-bioreactor).

3.2 Prospect of Membrane Integration in Photo-Bioreactor

The membrane for conventional CO2 capture should have high permeability for pure CO2 gas in the range of 1100–2200 Barrer [A Barrer is a non-SI unit of gas permeability through the membrane. One Barrer is 846 standard mL of gas passed through a membrane with 1 mm thick and 1 cm^2 area under 1 bar of differential pressure in 1 day], high CO2/N2 selectivity as in polyaniline or polyvynil alcohol membrane, high thermal and chemical resistance to avoid membrane destruction at above 100 °C; high plasticization resistance to avoid membrane swelling at pressures as high as 10 atm; high aging resistance to maintain separation performance; and cost-effective and cheaply manufactured for upscaling under different membrane modules and arrangements.

Ionic liquids can be used to treat higher concentrations of CO2 in flue gas, because of their high solubility [31]. Tang et al. (2005) [32] provided that CO2 adsorption in polyionic liquids was up to 7 times greater than in ionic liquids. Other than that, Chen et al. (2011) [33] have used an immobilized liquid membrane (glycerol-based) to improve membrane selectivity. As a result, the CO2/N2 separation factor at 0.5% of CO2 was observed to be over 5000. However, brittleness and easily degraded at room temperature are the main problem in polyionic liquid membranes.

Based on Yang et al. (2008) [34], polyethylene-imine showed excellent performance at capturing CO_2. It has branches of –NH2 functional groups which have the capability of spreading the CO_2 reaction in the polymer to allow high performance of capturing process. Moreover, cellulose acetate and polyimide membranes are more commonly

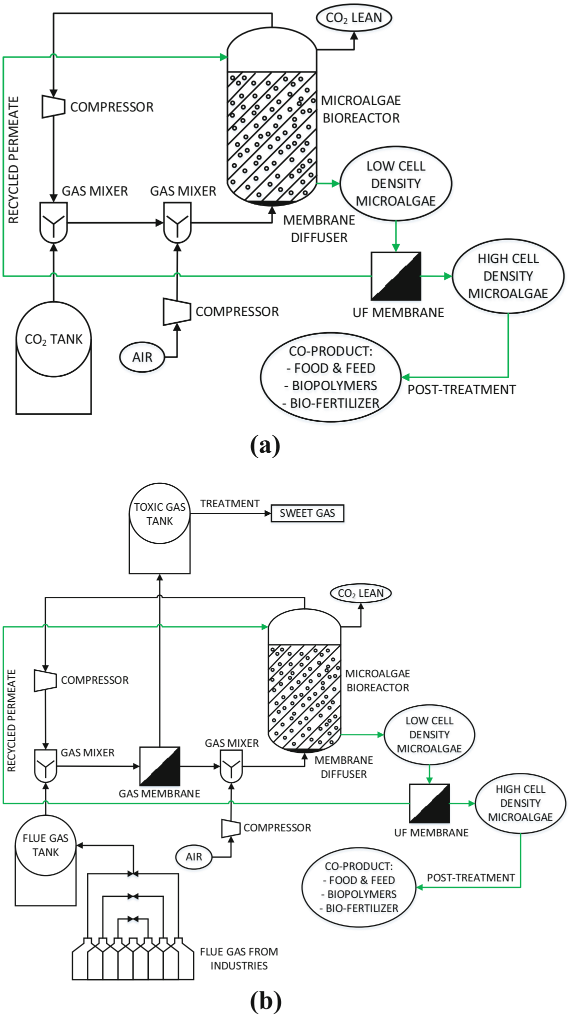

Fig. 3. **a.** Process flow diagram of lab-scale membrane integration in photo-bioreactor for CO2 capture **b.** Process flow diagram of industrial-scale membrane integration in photo-bioreactor for CO_2 capture

used in commercial CO_2 separation. The permeability of CO_2 across those membranes is 10 and 13 Barrer, respectively.

For the integration of membrane in a photo-bioreactor, the membrane acts as CO_2 separation agent as well as CO_2 microbubbles generator or membrane diffuser [18]. A membrane diffuser produces high gas mass transfer constant than other diffusers and bubbling techniques. It can accelerate the mass transfer of CO_2 into the culture medium, reduce CO_2 transport resistance, and enhance the CO_2 dispersion in the medium. The membrane material should tough, durable, easy to install, provide an acceptable CO_2 concentration with maximum concentration, and has low fouling phenomenon. The proposed lab-scale and industrial-scale process flow diagrams for cultivating microalgae in membrane photo-bioreactor are depicted in Fig. 3.

As a consequence of the low concentration of CO_2 in the atmosphere which is not sufficient for microalgae cultivation, appropriate and selective membrane material for continuously capturing CO_2 needs to be developed. From the previous description, the polymeric membrane material containing N compounds is nominated to be chosen. The CO_2 capturing with hollow fiber membrane integrated with the cultivation of Nannochloropsis sp. Gave excellent gas transfer, uniform mixing, and low hydrodynamic stress [28]. Several studies of CO_2 capture using microalgae in photo-bioreactor and membrane photo-bioreactor are outlined in Table 5. It is seen that membrane photo-bioreactor gave higher results compared to conventional photo-bioreactor. The integrated membrane concept thus has a more promising prospect for CO_2 capture.

Table 5. Distribution of the phylum Echinodermata at research stations

Photo-bioreactor Types	Microalgae Species	Result Specifications	Value	References
Airlift	*Botryococcus braunii*	CO2 Fixation Rate (g/L/day)	>1	Bilad et al., 2014; Chang and Yang, 2003 [35, 36]
	Chlorella sp.		0.109–0.264	
	Chlorella vulgaris		0.28–0.89	
	Nannochloropsis sp.		0.325–0.953	
Flat Panel	*Chlorella sp.*	CO2 Fixation Rate (g/L/day)	0.65–1.08	Klinthong et al., 2015; Chang and Yang, 2003 [36, 37]
	Dunaliella sp.		1.50–3.42	
	Nannochloropsis sp.		0.225–0.270	
PVDF Hollow Fiber Membrane	*Nannochloropsis sp.*	CO_2 Fixation Rate (g/L/day)	0.2–150	Bilad et al., 2014; Chen et al., 2011 [33, 35]
		Flux Recovery (%)	95	
PVC Hollow Fiber Membrane	*Tetraselmis suecica*	CO_2 Fixation Rate (g/L/day)	0.42–32.76	
		Flux Recovery (%)	>98	
PAN Flat Sheet Membrane	*Arthrospira platensis*	CO_2 Fixation Rate (g/L/day)	4.5–10	Chen et al., 2011 [33]
	Chlorella vulgaris		0.2–2	
	Cylindrotheca fusiformis	Total Cell (10^6 cells/mL)	2–4	Bilad et al., 2014; Zhao et al., 2015; Chen et al., 2011 [33, 35]
PVDF Flat Sheet Membrane	*Scendesmus quadricauda*	CO_2 Fixation Rate (g/L/day)	1–154.85	Zhao et al., 2015; Bilad et al., 2014 [20, 35]
		Flux Recovery (%)	>98	
PES-PVP Flat Sheet Membrane	*Nannochloropsis oculata*	CO_2 Fixation Rate (g/L/day)	1.49–2	Chen et al., 2011 [33]

(*continued*)

Table 5. (*continued*)

Photo-bioreactor Types	Microalgae Species	Result Specifications	Value	References
PVDF Flat Sheet Membrane	*Phaeodactylum tricornutum*	CO_2 Fixation Rate (g/L/day)	0.23	
PTFE Flat Sheet Membrane	*Chlorella vulgaris*	CO_2 Fixation Rate (g/L/day)	2.1	Bilad et al., 2014; Chen et al., 2011; Carvalho and Malcata, 2001 [33, 35, 38]
PET-PVDF Flat Sheet Membrane			1.2–1.4	
Ceramic Flat Sheet Membrane	*Chaetoceros calcitrans*	CO_2 Fixation Rate (g/L/day)	0.063	Bilad et al., 2014; Chen et al., 2011 [33, 35]
	Nannochloropsis gaditana		0.095	
	Phaeodactylum tricornutum		0.075	
PVDF Flat Sheet Membrane + Magnetically Induced Membrane Vibration	*Phaeodactylum tricornutum*	CO_2 Fixation Rate (g/L/day)	0.25	
	Chlorella vulgaris			
Hydrophilic PES Hollow Fiber Membrane	*Chlorella vulgaris*	Total Cell (10^6 cells/mL)	1.2–2.0	Harun et al., 2012; Bilad et al., 2014 [35, 39]
	Scenedesmus quadricauda			
	Scenedesmus dimorphus			
Hydrophilic PVC Flat Sheet Membrane	*Chlorella vulgaris*	CO_2 Fixation Rate (g/L/day)	0.5–2.5	Bilad et al., 2014 [35]
Membrane Carbonation	*Chlorella vulgaris*	Max CO_2 Tolerance (%)	1	Kumar et al., 2011; Ferreira et al., 2013 [25, 40]
	Nannochloropsis sp.		1.5–10	
	Scendesmus obliquus		100	
	Spirulina plantesis		2–15	

4 Conclusion

The perspective of CO_2 capture using microalgae bioreactor (photo-bioreactor) is attractive. By utilizing CO_2 from flue gas, this kind of process can sweeten flue gas, minimize the greenhouse effect, and lead to a sustainable environment. Besides the environmental advantages, it has a potency for producing many valuable products such as bioethanol, food & feed, biopolymer, bio-fertilizer, biogas, and biodiesel. The microalgae strain, types of photo-bioreactors, nutrient composition, CO_2 concentration, temperature, pH, light intensity, illumination cycle, and the presence of toxic gas affect the capture performance. This article also disclosed the potential of membrane integration with the microalgae cultivation process, usually called membrane photo-bioreactor. It has advantages comprising easy-to-install and generates microbubbles that provide excellent CO_2 mass transfer distribution into the medium, resulting in a higher CO_2 fixation rate. The membrane should durable, resistant to alkaline and acidic conditions, and have low fouling potential. Still, employing membranes coated with amine compounds improves the performance of capturing process. Finally, the membrane integration in the photo-bioreactor has the interesting prospect to obtain high productivity of microalgae as well as remediate the environment.

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