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Design of batch algal cultivation systems and ranking of the design parameters

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Abstract

In this article, we developed a process to design batch algal cultivation systems consisting of outdoor ponds, indoor photobioreactors (PBRs), outdoor PBRs, and indoor ponds for both freshwater and industrial wastes (wastewater and flue gas). We considered pH, temperature, light conditions, carbon, nutrients, inhibitors, mixing, and O_2 degassing as design parameters and sequentially ranked them according to the necessity of cultivation conditions. Although each set of conditions warrants a unique design according to the requirements, some scenarios were common for every system, i.e., microalgae species, temperature, pH, light, size, shape, and material were always ranked before nutrients, and mixing technique and inhibitors were consistently ranked after nutrients. Light and temperature for outdoor conditions, pH for ponds, and nitrogen and phosphorus were deemed noncontrollable. Ponds do not require material for construction; O_2 degassing and the selection of microalgae were always ranked first; and SO_x and NO_x were considered only for industrial flue gas. We constructed cultivation models of *Chlorella vulgaris* (*C. vulgaris*) for Bangkok based on the developed designs of algal cultivation systems. Monod's model (mathematical model) and simulations by SuperPro Designer software using the optimum parameter values predicted a maximum algal productivity of 0.0114–0.0381 and 0.11–0.7 g/l/day (open pond and PBR, respectively), bioremediation of 52–70% and 81–90% (open pond and PBR; only wastewater), and CO_2 biofixation of $< 1\%$ (only PBR). A comparison between the results found in this study and the literature on *C. vulgaris* suggests that both Monod's model and simulation software can predict algal productivity and bioremediation, but they are not recommended for CO_2 biofixation.

AQ1

AQ2

Keywords

Chlorella vulgaris
Microalgae cultivation
Wastewater
SuperPro designer

PBR
Open pond
Hybrid algal cultivation system

1. Introduction

Microalgae are a potential source of bioenergy, i.e., biodiesel, biogas, bioethanol, and biohydrogen are potential products derived from algal biomass (Slade and Bauen 2013). However, the current commercial usage of microalgae is mainly limited to the production of animal feed, fish feed, human food supplements, etc. (Spolaore et al. 2006; Bishop and Zubeck 2012). Microalgae were commercially used in nutraceuticals (23%), food (5%), cosmetics (12%), pharmaceuticals (12%), chemicals (12%), fertilizers (5%), animal feed (10%), and other applications (21%) in 2017 (WGR 2018). The availability of vitamins such as A, B1, B2, B12, C, and E; omega 3; nicotinate; biotin; folic acid; and pantothenic acid (Luiten et al. 2003; Spilling et al. 2015) in microalgae is the main reason for their use as food or a food ingredient. Other uses include ingredients of raw materials for skincare creams, anti-irritant creams, antiaging creams, etc. (Spolaore et al. 2006; Chen et al. 2010; Harun et al. 2010). North America (37%), Asia Pacific (32%), and Europe (22%) possess the greatest market share of microalgae (WGR 2018).

Outdoor open ponds and indoor PBRs, two widely used microalgae cultivation systems, are used for commercial algal cultivation (Sarker and Salam 2019). Open ponds can also be set up indoors, and PBRs can be installed outdoors. Similar to plants, the growth of microalgae requires nutrients such as nitrogen (N), phosphorus (P), and carbon (C). Chemicals, fertilizers, or CO_2 can provide nutrient C. Industrial flue gas, raw biogas from anaerobic digesters, untreated natural gas from gas wells, etc., which contain CO_2 can serve as a C source. One advantage of microalgae cultivation systems is that they can produce biomass and capture CO_2 simultaneously in the same operation unit without additional processes or chemicals (Sayre 2010), whereas traditional CO_2 removal processes require solvents that produce no value-added products (Sarker 2016).

The culture medium for cultivation can be prepared with either freshwater or wastewater. Microalgae cultivation reduces or removes ammonium, nitrate, nitrite, phosphate, and organic carbon from wastewater because microalgae consume these

elements as growth nutrients. Traditional wastewater treatments use chemicals for the treatment process, requiring a significant operation cost (Sarker and Sarkar 2018). The integration of wastewater with algal cultivation not only treats the wastewater but also offers several benefits, such as reductions in the water footprint and cultivation cost by reducing the use of fertilizers or any other nutrients for cultivation (for freshwater) or chemicals (for wastewater treatment). Many experimental works on measuring the optimum growth have considered only three or four parameters, such as light intensity, light/dark cycle, and temperature while other parameters were kept constant (Khoeyi et al. 2012; Rasdi and Qin 2015; Pham et al. 2017). However, commercial cultivation requires every possible parameter to be considered.

In this study, we used SuperPro Designer software. This software was initially used widely in bioprocessing, but later, its scope extended to include small-molecule active pharmaceutical ingredients and secondary pharmaceutical manufacturing processes (Ende 2010). To date, only a few works have been conducted on microalgae growth using SuperPro Designer, i.e., Asiedu et al. (2018) performed a technoeconomic analysis of the flash hydrolysis of microalgae, Qiu (2014) performed a life cycle analysis of microalgae liquefaction, and Dr. Daniel Klein-Marcuschamer (Joint BioEnergy Institute in Emeryville, CA, Jan 2015–Dec 2015) developed a model of microalgae production, purification, and conversion to lipids and found that tripalmitin and triglycerides of palmitic acid were the products.

The design process involves the use of a series of sequentially ordered steps to find a solution to a problem. Every step of algal cultivation design requires establishing the optimum conditions for each parameter. We determined the sequence of steps according to the dependence of relevant parameters on other parameters. If the parameters are not designed properly, determining the optimum algal growth will be difficult. We opted for *C. vulgaris* as an example and formulated designs for its cultivation in Bangkok based on our findings on the ranking of parameters. Then, we determined the theoretical algal productivity, bioremediation, and biofixation of CO_2 of *C. vulgaris* with simulations and mathematical models using the optimum conditions for *C. vulgaris* and checked the validity of the mathematical models and simulation software by comparing the calculated results with experimental findings. After that, design conditions for *C. vulgaris* were selected using the design parameters and their rankings. We evaluated the designs for *C. vulgaris* cultivation with mathematical models and SuperPro Designer software and estimated the algal growth rate with Monod's mathematical models in Microsoft Excel and algal density with SuperPro Designer. The novelty of this study consists of the design of algal cultivation systems by determining the parameters required for batch media under different conditions, i.e., an indoor pond,

outdoor pond, indoor PBR, and outdoor PBR, with both freshwater and wastewater as media and the ranking of parameters according to their importance and dependence on other parameters.

2. Methodology

The design parameters, rankings, and relevant formulas and constants were found by reviewing the literature. Priority was given to the recently published works.

Formulas for the mathematical model of the algal growth rate were chosen based on Monod's model because Monod's model is a straightforward approach to calculate the growth rate in water under limited nutrient conditions. All empirical constants in the following formulas are strictly limited to *C. vulgaris*.

Growth rate for light intensity:

$$\mu_{\mathrm{I}} = \mu_{\mathrm{mI}} \times \frac{I}{K_{\mathrm{I}} + I} \quad \text{(Buriew 1953)} \tag{1}$$

In Eq. (1), μ_{I}, μ_{mI}, I, and K_{I} represent growth rate (time^{-1}), maximum specific growth rate (time^{-1}), intensity, and half saturation constant (unit is same as intensity) of light, consecutively.

Growth rate for nitrogen:

$$\mu_{\mathrm{N}} = \mu_{\mathrm{mN}} \times \frac{S_{\mathrm{N}}}{K_{\mathrm{N}} + S_{\mathrm{N}}} \quad \text{(Novak and Brune 1985)} \tag{2}$$

In Eq. (2), μ_{N}, μ_{mN}, S_{N}, and K_{N} represent growth rate (time^{-1}), maximum specific growth rate (time^{-1}), concentration and half saturation constant (unit is same as concentration) of N, consecutively.

Growth rate for phosphorus:

$$\mu_{\mathrm{P}} = \mu_{\mathrm{mP}} \times \frac{S_{\mathrm{P}}}{K_{\mathrm{P}} + S_{\mathrm{P}}} \quad \text{(Monod 1949)} \tag{3}$$

In Eq. (3), μ_{P}, μ_{mP}, S_{P}, and K_{P} represent growth rate (time^{-1}), maximum specific growth rate (time^{-1}), concentration, and half saturation constant (unit is same as concentration) of P, consecutively.

Growth rate for carbon:

$$\mu_{\mathrm{c}} = \mu_{\mathrm{mC}} \times \frac{S_{\mathrm{c}}}{K_{\mathrm{c}} + S_{\mathrm{c}}} \quad \text{(Monod 1949)} \tag{4}$$

In Eq. (4) μ_{C}, μ_{mC}, S_{c}, and K_{c} represent growth rate (time^{-1}), maximum specific growth rate (time^{-1}), concentration, and half saturation constant (unit is same as concentration) of C, consecutively.

Overall growth rate when all factors are employed together:

$$\mu = \left[\frac{1}{\frac{K_{\mathrm{I}}}{I} + \frac{K_{\mathrm{C}}}{S_{\mathrm{C}}} + \frac{K_{\mathrm{N}}}{S_{\mathrm{N}}} + \frac{K_{\mathrm{P}}}{S_{\mathrm{P}}}}\right] \times \left[\left(\mu_{\mathrm{I}} \times \frac{K_{\mathrm{I}}}{I}\right) + \left(\mu_{\mathrm{c}} \times \frac{K_{\mathrm{C}}}{S_{\mathrm{C}}}\right) + \left(\mu_{\mathrm{N}} \times \frac{K_{\mathrm{N}}}{S_{\mathrm{N}}}\right) + \left(\mu_{\mathrm{p}} \times \frac{K_{\mathrm{P}}}{S_{\mathrm{P}}}\right)\right] \quad \text{(Mankad and Bungay 1988; Jalalizadeh 2012)} \tag{5}$$

In Eq. (5), μ represents overall algal growth rate (time^{-1}).

Number of moles of carbon in the carbon dioxide transferred to the aqueous medium:

6

$$M_{CO_2} = \frac{Q \times C \times \tau}{V_m} \quad \text{(Couto et al. 2018)}$$

In Eq. (6), Q, C, τ, and V_m represent flowrate of the gas (volume/time), the concentration of CO_2 in the gas flow (%), duration of gas flow (time), and molar volume at 1 atm and 25 °C (l mol^{-1}), consecutively.

SuperPro designer also uses Monod's model for algae-related simulations. The maximum limiting reactant conversion for the PBR was 90%, and 70% was selected for the open pond. The chemical formula for algal biomass was $C_{106}H_{263}O_{110}N_{16}P$ (Stumm and Morgan 1996; Dalrymple et al. 2013). The selected temperature was 25 °C, and the pressure was 1 atm. The stoichiometric reaction in freshwater cultivation is as follows:

$$[\text{DAP} + (99 \times \text{Bicarbonate}) + (7 \times \text{Urea}) + (63.5 \times \text{Water})] = [\text{Algal biomass} + (130.75 \times \text{Oxygen})] \quad (7)$$

The stoichiometric reaction in wastewater cultivation is as follows:

$$[(8 \times \text{Ammonium nitrate}) + \text{Phosphate} + (106 \times \text{Carbon dioxide}) + (115.5 \times \text{Water})] = [\text{Biomass} + (122.75 \times \text{Oxygen})] \quad (8)$$

We used different types of wastewaters for the wastewater-integrated systems, such as domestic, poultry feedlot, swine feedlot, paper mill, and tannery wastewater. We used the N and P contents of these wastewaters from the study of Christenson and Sims (2011). In the simulations, we selected stoichiometrically balanced reactions for both the open and controlled systems and considered only the material balance.

3. Design of microalgae cultivation systems

3.1. Effect of temperature

Temperature influences the algal growth mechanism, cell size, biochemical composition, and nutrient requirements (Juneja et al. 2013). The optimum temperature corresponds to the maximum growth rate (Renaud et al. 2002), minimal cell size (Rhee 1982; Harris 1987; Ras et al. 2013; Skau et al. 2017), and maximum carbon and nitrogen utilization efficiency (Buggeln 1983; Ras et al. 2013). Reports suggest that changes in cytoplasmic viscosity under suboptimal temperature conditions are responsible for less efficient carbon and nitrogen utilization (Hope and Walker 1976; Raven and Geider 1988; Skau et al. 2017). The effect of light on algal growth also depends on temperature (Juneja et al. 2013). At a fixed light intensity, a lower temperature reduces electron transport because of the decreased rate of CO_2 fixation (Vonshak and Torzillo 2003). Additionally, the active oxygen species experience an inhibition effect at a lower temperature, and the photoinhibition effect is decreased by protecting PSII (Vonshak and Torzillo 2003). The synthesis process of D1 protein becomes slower during photoinhibition at a lower temperature, which results in the PSII repair cycle (Vonshak and Torzillo 2003). When the temperature is higher than optimal, it slows down the growth rate by reducing protein synthesis (Konopka and Brock 1978; Ras et al. 2013).

3.2. Effect of pH

pH determines the availability and solubility of CO_2, carbonaceous species, and other essential nutrients in the culture medium (Goldman and Shapiro 1973; Azov 1982; Chen and Durbin 1994; Morales et al. 2018) and influences algal metabolism (Goldman and Shapiro 1973; Chen and Durbin 1994; Ismaiel et al. 2016). The maximum growth of algal biomass is achieved at the optimum pH. Any deviation from optimum pH conditions causes a decreased algal growth rate due to metabolic inhibition (Goldman et al. 1982; Ismaiel et al. 2016). When the pH value exceeds the optimum limit, algae obtain less C from CO_2, causing less growth (Azov 1982; Chen and Durbin 1994; Boatman et al. 2018). Under this condition, the affinity of microalgae toward free CO_2 also decreases (Azov 1982; Rotatore and Colman 1991; Boatman et al. 2018). Similarly, when the pH is lower than the optimum level, it can alter nutrient uptake (Gensemer et al. 1993; Boatman et al. 2018) or induce metal toxicity (Sunda 1975; Anderson and Morel 1978; Ismaiel et al. 2016) and eventually affects algal biomass growth negatively. Lower pH decreases nitrogen and phosphorus removal due to pH-dependent processes (Luiten et al. 2003; de-Godos et al. 2012). Temperature influences light, CO_2, and other nutrients. On the other hand, pH influences other parameters, except for light, in ways similar to temperature. Therefore, in this study, the temperature was selected as the most influential parameter, followed by pH.

3.3. Effect of light

Light quality, light intensity, and light/dark cycle play important roles in algal growth. Light quality (light wavelength or color) should be determined first, followed by light intensity and light/dark cycle (Wong 2016; Xu et al. 2016). Light quality means the light wavelength. The range of wavelengths of light can be predicted through light color. A 14:10 light/dark cycle means that in a 24-h period, the culture medium receives continuous light for 14 h, followed by 10 h of continuous dark, and this cycle repeats until the cultivation ends. One study suggests that light intensity also has an impact on the nutrient ratio (Spilling et al. 2015). Light affects the C/N, C/P, and C/Chl ratios and other cellular components, such as the protein content and lipid fraction, especially during exponential growth. A light intensity higher or lower than the optimum intensity moves the stoichiometric ratio further away from the optimum ratio and thus changes the nutrient ratio (Spilling et al. 2015).

3.4. Effect of nutrients and other parameters

The gas hold up, mixing time, coefficient of gas and liquid mass transfer, shear stress, flow rate, etc., are dependent on the PBR shape (Pham et al. 2017). The light distribution can be influenced by the shape and selected material of PBRs. An optimum amount of C, N, and P induces optimum growth (Shashirekha et al. 2016), as indicated by the C/P, C/N, and N/P ratios (Laws and Bannister 1980; Hillebrand and Sommer 1999; Geider and La-Roche 2002; Hessen et al. 2002; Pahlow 2005; Novoveská et al. 2016; Flynn et al. 2017). No study has concluded that the effect of C, N, or P on algal growth involves mutual interactions; therefore, the optimum nutrient contents can be measured in parallel. The source of C can be carbonates or CO_2. Chemicals such as nitrate, ammonium, phosphate, or fertilizers containing N and P can be sources of N and P for algal cultivation (Bajpai et al. 2014). Considering cost, availability, and usability, CO_2 and fertilizers are preferred for commercial cultivation (Markou et al. 2014), where the nutrient ratio can be maintained appropriately. Commercial algal cultivation requires proper mixing because it governs cell movement between dark and illuminated zones and influences mass transfer in the culture (Guo et al. 2015). The mixing process can be conducted by aeration (suitable only for a closed system) or by mechanical agitation (applicable for both open and closed systems); it can also be continuous or intermittent. Like other plants, microalgae produce O_2, which limits algal growth (Sousa et al. 2013a, b; Guo et al. 2015); but, O_2 degassing is required only for PBRs because of their closed structure. NO_x and SO_x also act as algal growth inhibitors (Crofcheck et al. 2013; Shihady 2014). Flue gas may contain NO_x and SO_x, and their tolerance limits for

microalgae should only be determined after determining the optimum conditions for nutrients, followed by mixing and finally O_2 degassing.

3.5. Ranking of the design steps

Table 1 reports the ranking of the design steps for eight types of algal cultivation systems. As the design process involves a series of steps, the optimum value of one or more parameters is determined in every step. The parameters were assigned numbers according to their priority. The number zero (0) indicates that the parameter is not controllable in the design, and a dash (−) indicates that particular parameter is not required in the design. In the case of open ponds (both freshwater and wastewater), temperature, pH, and light parameters cannot be controlled; microalgae species are selected based on these parameters. Then, the size and shape of the pond are determined, followed by the amount of nutrients (C, N, and P), the nutrient supply procedures, and the mixing technique. Figure 1 summarizes the process flow diagram for an open freshwater pond. Temperature and light parameters are not controllable in outdoor PBRs because they are dependent on specific geographic locations. Microalgae species are selected based on these parameters. pH is chosen according to the tolerance level of the selected microalgae. Then, the material for the construction of the PBR is selected, followed by the size, shape, nutrients, mixing technique, and O_2 degassing technique. Figure 2 summarizes the process flow diagram for a freshwater outdoor PBR. The difference between indoor and outdoor ponds is that temperature and light parameters are controllable in an indoor pond, and the sequence is first light color, followed by light intensity and light/dark cycle. Figure 3 summarizes the process flow diagram for an indoor freshwater pond. An indoor PBR is a completely controlled system. Microalgae species are selected first. Any species of microalgae can be chosen in this system because every parameter is controllable. Figure 4 shows the process flow diagram for a controlled PBR with industrial waste.

Table 1

Design of microalgae cultivation systems with the freshwater and wastewater

Parameters	Open pond		Outdoor PBR		Indoor pond		Indoor PBR	
	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes

Parameters	Open pond		Outdoor PBR		Indoor pond		Indoor PBR	
	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes
Selection of microalgae species	1	1	1	1	1	1	1	1
Temperature	0	0	0	0	2	2	2	2
pH	0	0	2	2	0	0	3	3
Size and shape	2	2	4	4	3	3	5	5
Material	–	–	3	3	–	–	4	4
Light color	0	0	0	0	4	4	6	6
Light intensity	0	0	0	0	5	5	7	7
Light/dark cycle	0	0	0	0	6	6	8	8
C concentration	3	3	5	5	7	7	9	9
C supply procedure	4	4	6	6	8	8	10	10
N concentration	3	0	5	0	7	0	9	0
N supply procedure	4	0	6	0	8	0	10	0
P concentration	3	0	5	0	7	0	9	0
P supply procedure	4	0	6	0	8	0	10	0
Mixing (by aeration/stirring)	5	6	7	8	9	10	11	12
Mixing time interval and duration	6	7	8	9	10	11	12	13
O_2 degassing	–	–	9	10	–	–	13	14

Parameters	Open pond		Outdoor PBR		Indoor pond		Indoor PBR	
	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes	Freshwater	Industrial wastes
Inhibitors (SO_x)	–	5	–	7	–	9	–	11
Inhibitors (NO_x)	–	5	–	7	–	9	–	11

Fig. 1

Process flow diagram of microalgae cultivation in freshwater open pond

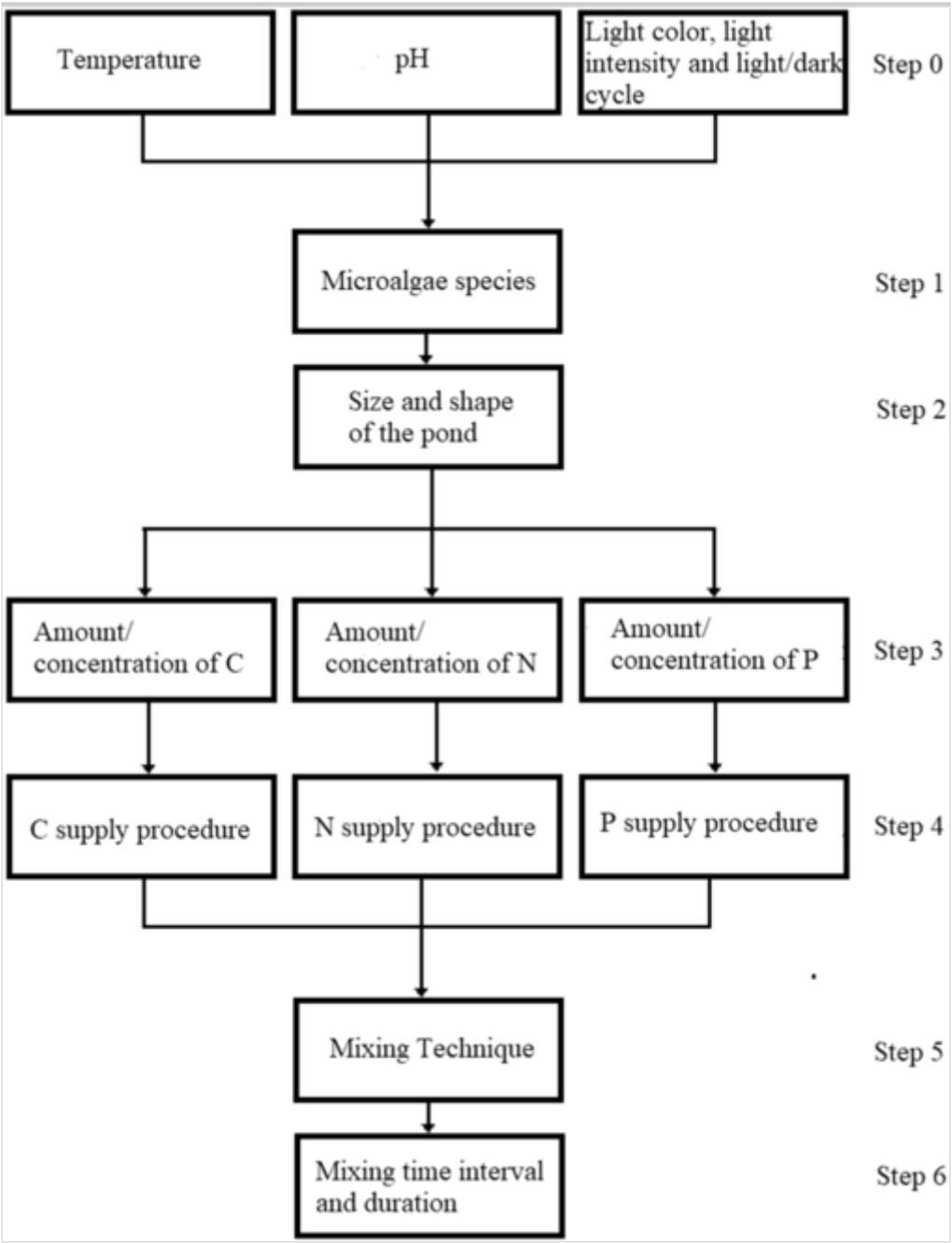

Temperature
pH
Light color, light intensity and light/dark cycle
Step 0
Microalgae species
Step 1
Size and shape of the pond
Step 2
Amount/ concentration of C
Amount/ concentration of N
Amount/ concentration of P
Step 3
C supply procedure
N supply procedure
P supply procedure
Step 4
Mixing Technique
Step 5
Mixing time interval and duration
Step 6

Fig. 2

Process flow diagram of microalgae cultivation in freshwater outdoor PBR

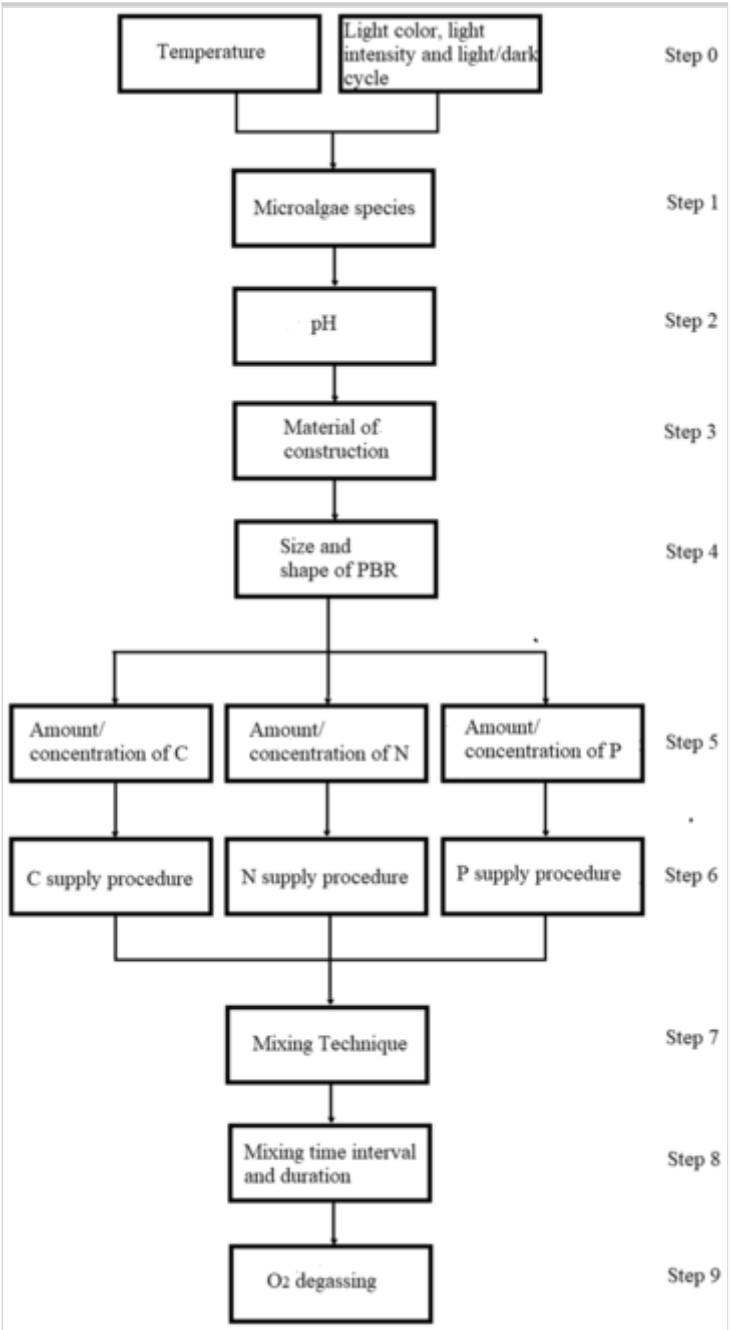

Temperature
Light color, light intensity and light/dark cycle
Step 0
Microalgae species
Step 1
pH
Step 2
Material of construction
Step 3
Size and shape of PBR
Step 4
Amount/ concentration of C
Amount/ concentration of N
Amount/ concentration of P
Step 5
C supply procedure
N supply procedure
P supply procedure
Step 6
Mixing Technique
Step 7
Mixing time interval and duration
Step 8
O2 degassing
Step 9

Fig. 3

Process flow diagram of microalgae cultivation in freshwater indoor pond

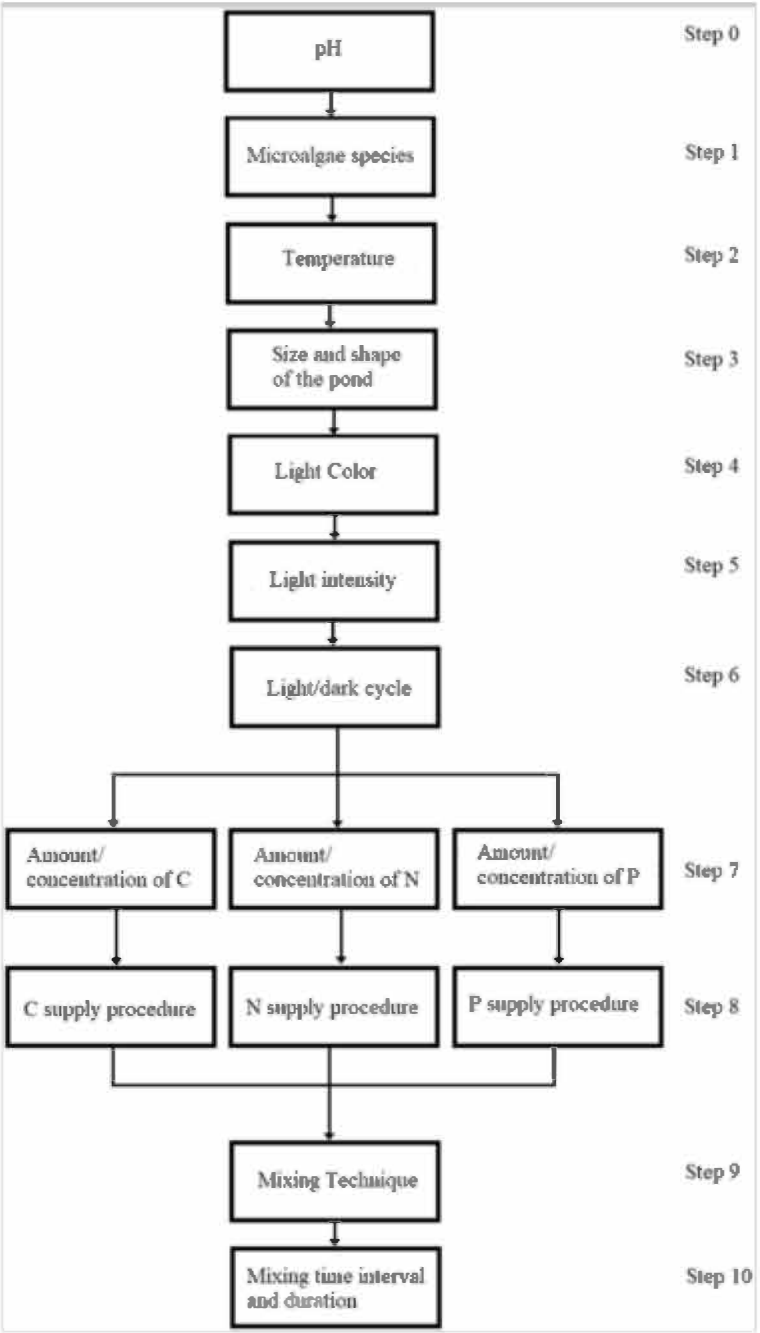
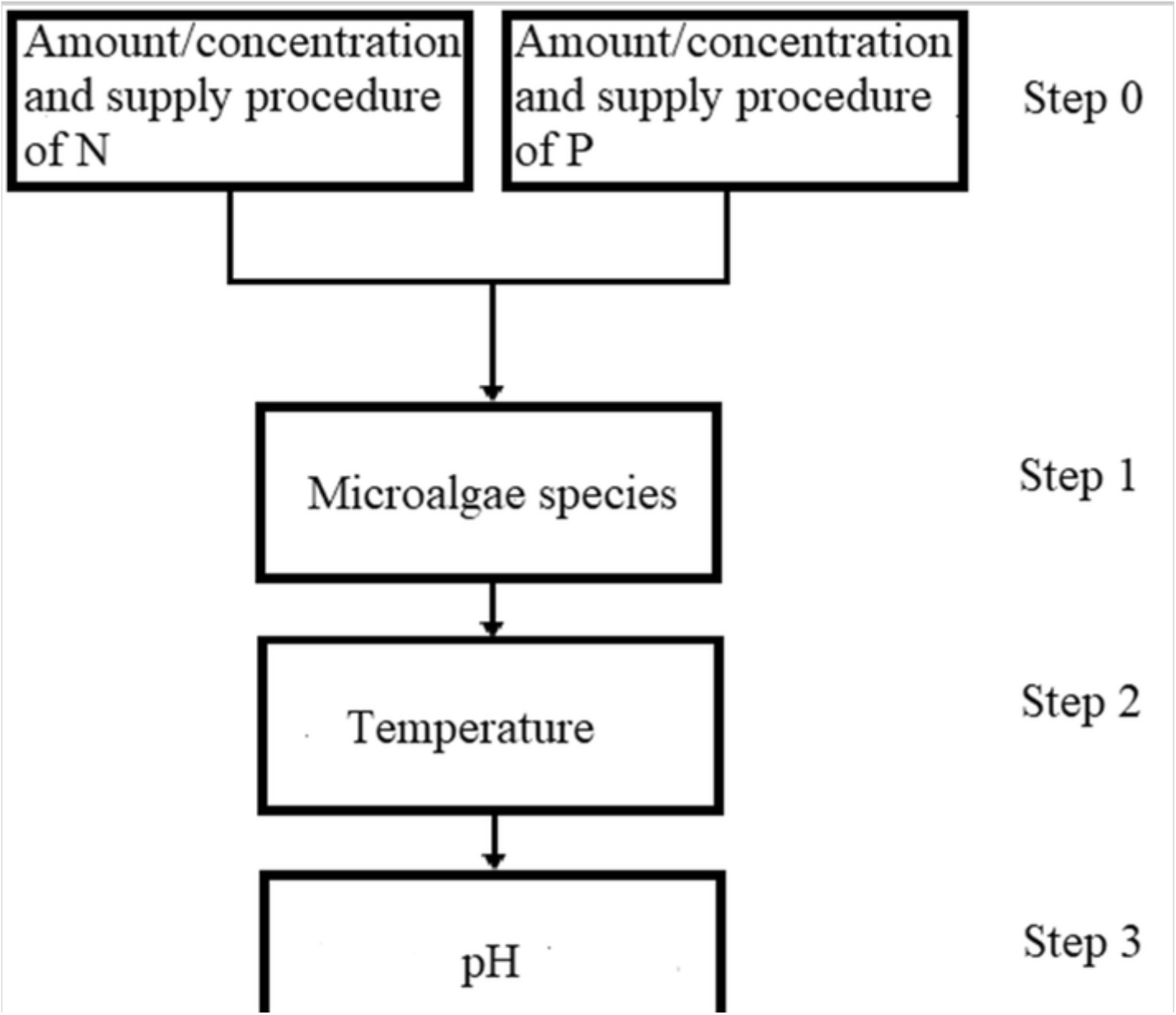
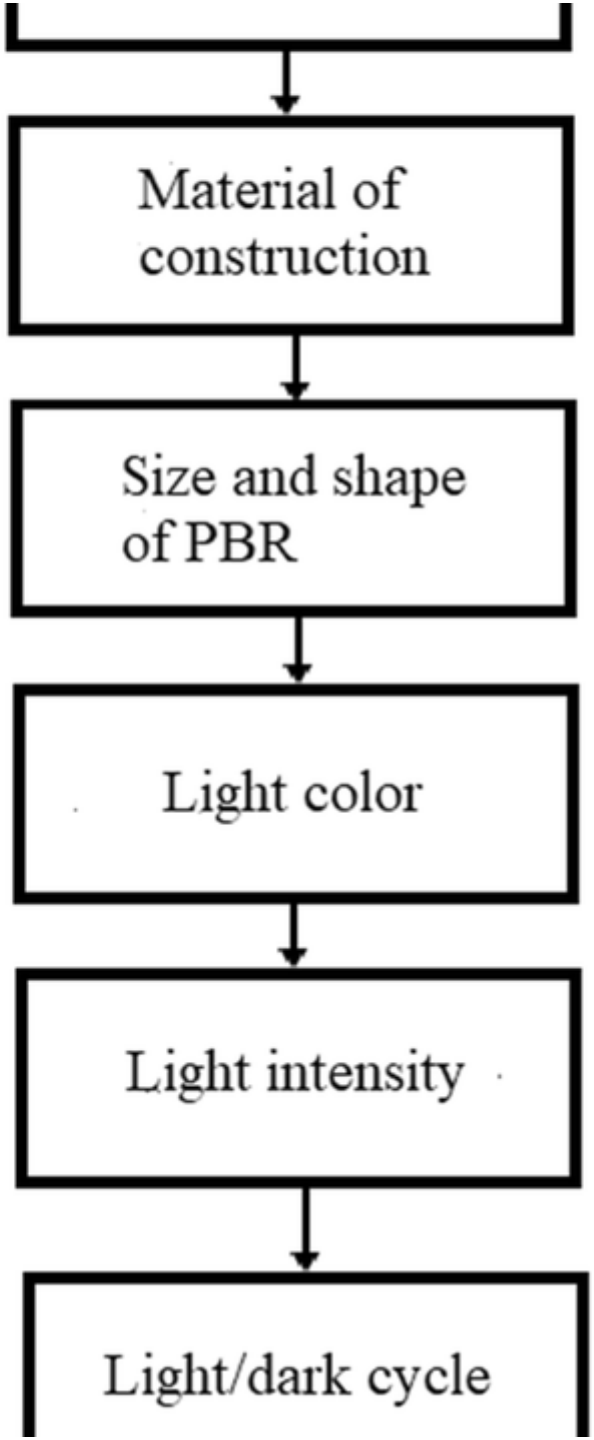

pH
Step 0
Microalgae species
Step 1
Temperature
Step 2
Size and shape of the pond
Step 3
Light Color
Step 4
Light intensity
Step 5
Light/dark cycle
Step 6
Amount/ concentration of C
Amount/ concentration of N
Amount/ concentration of P
Step 7
C supply procedure
N supply procedure
P supply procedure
Step 8
Mixing Technique
Step 9
Mixing time interval and duration
Step 10

Fig. 4

Process flow diagram of microalgae cultivation in controlled PBR with industrial wastes





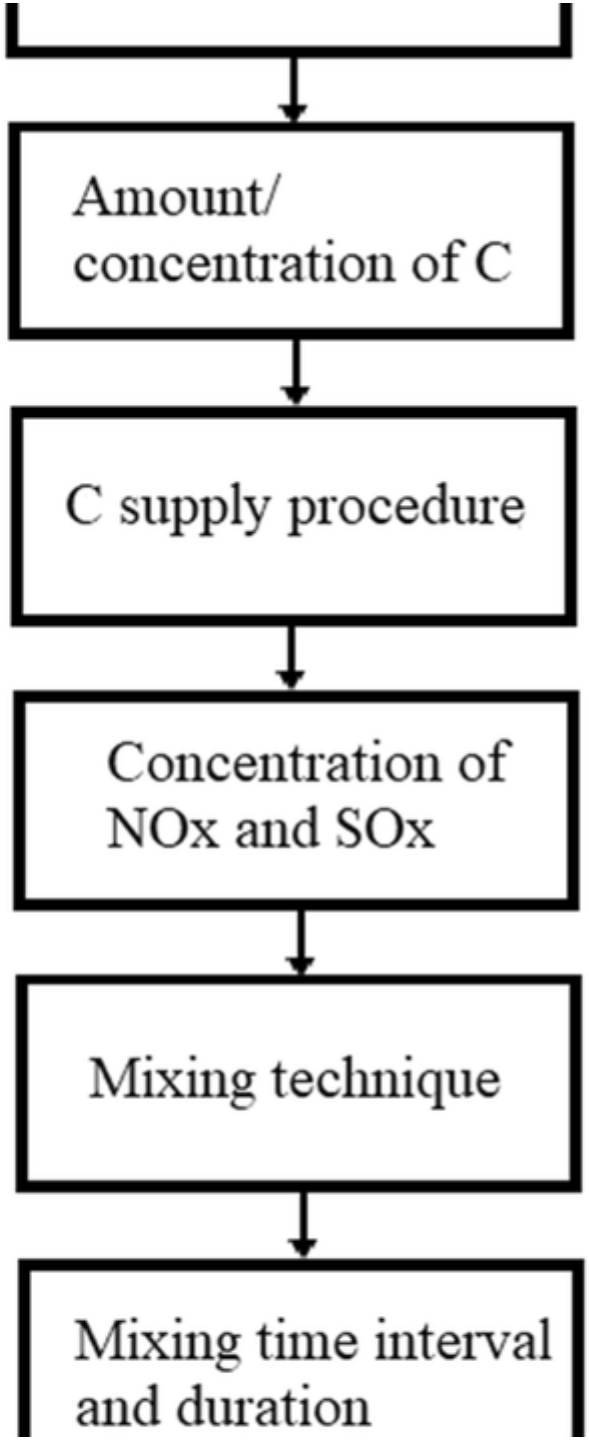
Step 4

Step 5

Step 6

Step 7

Step 8



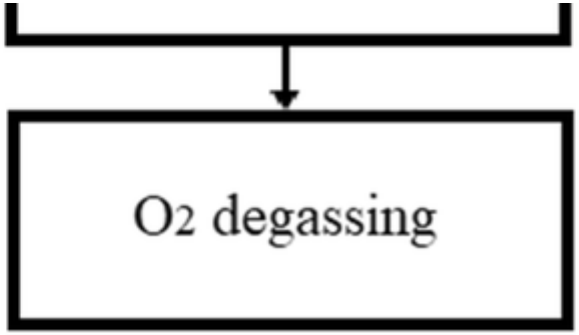
Step 9

Step 10

Step 11

Step 12

Step 13



An optimum nutrient ratio is not available in wastewater, but this medium offers several benefits, such as nutrients will be available at free of cost and algae cultivation will reduce pollutants, such as total nitrogen, total phosphorus, BOD, and COD. (Sousa et al. 2013a; Luo et al. 2016). Wastewater can be adjusted to the optimum nutrient conditions, but it will not be supportive of cost reduction and wastewater treatment. For example, 1 kg of algal biodiesel may require approximately 3500 kg of freshwater (Farooq et al. 2015; Feng et al. 2016); this quantity can be reduced to zero by using wastewater. In this study, nutrient adjustment was not considered, and therefore, the amount of N and P was assumed uncontrollable. Additionally, in this design, the systems for industrial wastes given in Table 1 were assumed to be supplied with flue gas and wastewater where flue gas provides CO_2, NO_x, and SO_x.

4. Algal cultivation design for Bangkok

The choice of microalgae species or cultivation system depends on several factors, i.e., geographic location, market price, chemical composition, extraction technology of components, demand for microalgae-derived products, etc. In this study, we considered only geographic location and potential usage. We selected Bangkok (the capital city of Thailand) as the location for this study. Bangkok is located in a hot and humid region. Most of the year, the average air temperature and relative humidity remain high. The mean dry bulb temperature of Bangkok ranges from 28.46 to 30.23 °C, and the relative humidity is between 70 and 76% (Srisuwan and Shoichi 2017). The range of monthly mean sunshine hours is 3.58 to 9.55 h/day, and the range of monthly mean global solar radiation (GSR) is 5.64 to 22.53 MJ/m^2/day (Waewsak et al. 2014). These conditions are suitable for the cultivation of *C. vulgaris* because the favorable temperature range for this species is 20 °C to 40 °C (Mayo 1997). This species has long been considered a source of protein and is now industrially produced

for human food and animal feed (Liu and Chen 2014). It is also rich in oil and is an ideal feedstock for biofuels (Liu and Chen 2014). Table 2 summarizes the optimum parameters of microalgae growth conditions.

Table 2

Optimum parameters for the cultivation of *Chlorella vulgaris* in open pond and PBR

Parameters	**Open pond**	**PBR**
Selection of microalgae species	*Chlorella vulgaris* (Mayo 1997; Cerón García et al. 2005; Yeesang and Cheirsilp 2014)	*Chlorella vulgaris* (Mayo 1997; Cerón García et al. 2005; Yeesang and Cheirsilp 2014)
Temperature	–	25 °C (Mitra et al. 2012)
pH	–	7.5 (range 7–8) (Serra-Maia et al. 2016; Sakarika and Kornaros 2016)
Depth	Depths of 0.2–0.5 m (Liang et al. 2015)	0.2 m diameter (Xu et al. 2009)
Area	The surface area of a single pond does not usually exceed 0.5 ha but can be more substantial. (Park et al. 2011)	–
Length and width	Length/Width (of pond) = 10 or larger (Chisti 2016)	–
Volume	The surface-to-volume ratio is always 1/(culture depth in the pond, m) (Park et al. 2011)	–
Size and shape	Raceway configuration may be a single loop or multiple loops around interior dividing walls. The pond bottom may be either lined or unlined depending on soil conditions and local regulations (Park et al. 2011)	The most common and popular types of closed PBRs are annular, tubular, plastic bag system, helical, airlift, pyramid, well system, flat plate, column, vertical column, bubble column, stirred-tank, immobilized bioreactors, rectangular tank, and hybrid system. (Rachlin and Grosso 1991; Carvalho et al. 2006)

Parameters	Open pond	PBR
Material	–	Anything that can fill these requirements can be PBR; possible materials can be silicate, glass, polyethylene (PE), polyvinyl chloride (PVC), polycarbonate (PC), and acrylic (Plexiglas, PMMA), etc. (Rachlin and Grosso 1991; Carvalho et al. 2006)
Light color	–	LED white light (Posten 2012; Mohsenpour et al. 2012)
Light intensity	–	60–100 μmol m^{-2} s^{-1} (Hultberg et al. 2014)
Light/dark cycle	–	16:8 (Khoeyi et al. 2012; Kendirlioglu et al. 2015; Khalili et al. 2015)
C concentration	Inorganic (bicarbonate): 1 g/l, organic C (glucose): 10–20–30 g/l or 7.22 mM (milli molar), CO_2: 10% (Kong et al. ~~2002~~2011; De-Assunção 2015; Kendirlioglu et al. 2015; Sharma et al. 2016)	Inorganic (bicarbonate): 1 g/l, organic C (glucose): 20–30 g/l or 7.22 mM (milli molar), CO_2: 10% (Kong et al. ~~2002~~2011; De-Assunção 2015; Kendirlioglu et al. 2015; Sharma et al. 2016)
C supply procedure	Batch (except CO_2), Continuous (only CO_2)	Batch, continuous
N concentration	Urea 0.75 g/l or 12.4 mM (Mokashi et al. 2016; Sharma et al. 2016)	Urea 0.50 g/l or 12.4 mM (Mokashi et al. 2016; Sharma et al. 2016)
N supply rate	Batch	Batch
P concentration	N/P ratio 10 (Chisti 2013)	N/P ratio 10 (Chisti 2013)
P supply rate	Batch	Batch
Mixing (by aeration/stirring)	Mixing is normally provided by a paddlewheel to give a mean horizontal water velocity of approximately 0.15–0.3 m/s (Choi and Lee 2015)	0.05 vvm (night)–0.2 vvm (day) (Demirbas 2010)
Mixing time interval and duration	Continuous	Continuous

Parameters	Open pond	PBR
O_2 degassing	Other than agitation by the paddlewheel, no oxygen removal mechanism is used in a typical raceway. In some cases, the culture may be sparged with air to control the buildup of oxygen. Despite a high surface area relative to the culture depth, the oxygen removal from raceway ponds is inadequate (Shilton 2006; Park et al. 2011; Chisti 2016)	As low as possible, with O_2 degasser (Zannoni and De Philippis 2014; Chen et al. 2015)
Inhibitors (SO_x)	90–120 ppm (Sousa et al. 2013b)	90–120 ppm (Sousa et al. 2013b)
Inhibitors (NO_x)	60 ppm (Crofcheck et al. 2013)	60 ppm (Crofcheck et al. 2013)

Although the optimum pH was 7.5, a reasonable growth rate and productivity were also found at pH values from 7 to 8. Setting pH at constant 7.5 with an automatic pH controller would require additional capital, operation (mostly energy consumption), and maintenance costs. However, maintaining the pH in a particular range (in this particular case, from 7 to 8) is easier because it can be done manually. Similarly, temperature control also costs money, and both the capital cost and energy consumption are significantly higher than those of automatic pH controller equipment. If the ambient environmental temperature is in a favorable range, temperature control is not required. However, the environmental temperature is subject to weather and seasons; depending on geographic location, the temperature can deviate to values lower or higher than the favorable range for a long time. In this particular situation, the installation of a temperature control system is necessary. Considering the average weather, a temperature control system is not required in Bangkok. Maintaining light intensity and light/dark cycles in indoor conditions is not difficult but maintaining the wavelength is difficult, especially in a laboratory. The main reason is the lack of availability of inexpensive equipment for measuring and controlling the wavelength. But, the range of wavelengths can be estimated by the light color because every color of light belongs to a specific range of wavelengths. Choosing an appropriate light color for algal growth is a challenge. Hultberg et al. (2014) reported that the maximum algal density was found with yellow light, followed by white and red light. However, Yan et al. (2013) reported that the highest growth rate of *C. vulgaris* and nutrient removal efficiency from wastewater was found with red light, followed by white and yellow light. Mohsenpour et al. (2012) reported that the maximum algal productivity was achieved with violet, green, and orange light, followed by white light (33.3% less than maximum) and red light (66.7% less than maximum). Wong (2016) reported that the maximum biomass growth and lipid production of *C. vulgaris* were obtained

when cool white light was used. Another important factor is energy consumption. The energy consumption of yellow, purple, green, and blue light is significantly higher than that of red and white light (Yan et al. 2013). In all the studies mentioned above, white light did not always show the best result but was better than most of the other lights. Therefore, in this design, white light is suggested.

Readily available, low-cost and durable transparent materials are preferred for the construction of PBRs. Initially, glass was the material most commonly used to build PBRs. Glass is durable but expensive. Other potential materials are polyethylene, polyvinyl chloride, polycarbonate, and acrylic (also known as Plexiglas or PMMA) (Posten 2012). Currently, research is ongoing to explore the potentiality of plastic bags to be used as materials of PBRs because plastic bags are cheap, readily available, and also reusing and recycling plastic materials will have a positive impact on nature and the climate (Pagliolico et al. 2017; Huang et al. 2017). We report two examples, a freshwater outdoor PBR and indoor pond with industrial waste, in Table 3, combining Tables 1 and 2.

Table 3

Design of *C. vulgaris* cultivation in freshwater outdoor PBR and indoor pond with industrial waste

Ranking	Freshwater outdoor PBR	Ranking	Indoor pond with industrial wastes
0	Temperature (weather dependent)	0	pH (as provided)
0	Light color (depends on sun)	0	N concentration (as provided)
0	Light intensity (depends on the sun)	0	N supply procedure (comes with wastewater)
0	Light/dark cycle (depends on sun)	0	P concentration (as provided)
1	Microalgae species—Chlorella *vulgaris*	0	P supply procedure (comes with wastewater)
2	pH-7.5	1	Microalgae species—*Chlorella vulgaris*
3	Materials of construction—any material that is transparent, durable and low cost	2	Temperature-25 °C

Ranking	Freshwater outdoor PBR	Ranking	Indoor pond with industrial wastes
4	Size and shape—Any size like annular, tubular, plastic bag system, helical, airlift, pyramid, etc. that can suit the overall process	3	Size and shape—Table 3 for depth, area, length, width, volume and shape of the pond
5	Concentration of C—Inorganic (bicarbonate): 1 g/l, organic C (glucose): 20–30 g/l	4	Light color—LED white light
6	C supply procedure—batch	5	Light intensity—60–100 µmol m^{-2} s^{-1}
5	Concentration of N—urea 0.50 g/l	6	Light/dark cycle—16/8
6	N supply procedure—batch	7	The concentration of C—10% CO_2
5	Concentration of P–N/P ratio 10	8	C supply procedure—continuous
6	P supply procedure—batch	9	The concentration of NO_x and SO_x: 60 ppm and 90–120 ppm
7	Mixing technique—aeration [0.05 vvm (night)–0.2 vvm (day)]	10	Mixing technique—mechanical mixing/agitation
8	Mixing time interval—continuous	11	Mixing time interval—continuous
9	O_2 degassing—any low-cost method		

5. Simulation and mathematical model

5.1. Algal growth

Monod's model calculates values for every medium in the same way. If the medium has a vast nutrient content, it will show a tremendous growth rate, as reflected in Tables 4 and 5, which show unusually high productivity in swine feedlot media because of the high availability of N and P. In physical experiments, the growth rate shows a positive correlation with nutrient availability below the optimum level. Beyond the optimum level, the additional nutrients not taken up by microalgae need to be recycled or treated. Therefore, Monod's model remains valid up to the optimum nutrient level.

Studies have found that the maximum algal biomass density, growth rate, and productivity obtained in open freshwater ponds were 0.3–1.0 g/l, 0.10–0.25 day^{-1}, and 0.075–0.1 g/l/day, respectively, and those in freshwater PBRs were 1.0–2.0 g/l, 0.14–0.5 day^{-1}, and 0.28–0.5 g/l/day (Tahir 2014; Whitton et al. 2015); these values are higher than our simulation results. Similarly, in some studies in both open and closed systems, the wastewater algal density, growth rate, and productivity were higher than those in our study (Lim et al. 2010). Both in the literature and in our simulation, PBRs always showed better performance, and the growth parameters in freshwater were higher than those in wastewater (except swine feedlot wastewater). Many laboratories use modern and complicated cultivation techniques and designs of open ponds or PBRs that are impossible to use in simulation, which was the main reason for the difference between our results and experimental results. Nevertheless, our results were close to those experimental results. In a freshwater system, N and P are provided in a balanced proportion, so maximum productivity was assumed. On the other hand, a wastewater system does not provide a balanced N/P ratio, which negatively affects algal growth. Rasdi and Qin (2015) reported that the biochemical composition depends on the N/P ratio (Rasdi and Qin 2015). However, Choi and Lee (2015) reported that no strong correlation was found between total nitrogen removal and algal growth but the removal of total phosphorus was strongly correlated with the N/P ratio and algal productivity.

Table 4

Algal cultivation simulation in open ponds and PBRs with freshwater and several wastewaters

Type of culture medium	Open ponds			PBRs		
	Growth rate (day^{-1})	Max. algal density (g/l)	Productivity (g/l/day)	Growth rate (day^{-1})	Max. algal density (g/l)	Productivity (g/l/day)
Freshwater	0.096	0.398	0.0381	0.405	0.509	0.2064
Domestic wastewater	0.066	0.154	0.0102	0.120	0.2	0.0240
Poultry feedlot	0.009	1.3	0.0114	0.065	1.681	0.1099
Swine feedlot	0.002	8.4	0.0199	0.064	10.852	0.6978
Paper mill	0.010	0.0156	0.0002	0.016	0.02	0.0003

Type of culture medium	Open ponds			PBRs		
	Growth rate (day^{-1})	Max. algal density (g/l)	Productivity (g/l/day)	Growth rate (day^{-1})	Max. algal density (g/l)	Productivity (g/l/day)
Tannery wastewater	0.017	0.351	0.0060	0.066	0.454	0.0300

Table 5

N and P removal efficiency of algal cultivation systems in open ponds and PBRs with different types of wastewater

Type of culture medium	CO_2 fixation (%)	N removal (%)		P removal (%)	
	PBR	Open pond	PBR	Open pond	PBR
Domestic wastewater	0.11	70.0	90.0	51.9	66.7
Poultry feedlot	0.81	29.4	37.8	70.0	90.0
Swine feedlot	5.14	62.9	80.9	70.0	90.0
Paper mill	0.03	25.6	33.0	70.0	90.0
Tannery wastewater	0.23	70.0	90.0	45.0	57.8

5.2. Bioremediation

A total of 90% of the limiting nutrients was consumed in the closed system, and 70% was consumed in the open system. The other components were consumed based on the N/P ratio in wastewater and the stoichiometric reaction given in Eqs. (7) and (8). Several studies report that N and P removals of 54–95% and 40–98%, respectively, were achieved in open ponds (Goldman et al. 1974; Wrigley and Toerien 1990; Aziz and Ng 1992; Cromar et al. 1992, 1996; Delrue et al. 2016; Brar et al. 2017; Lian et al. 2018) and removals of 56–99% and 55–97%, respectively, were achieved in closed systems

(Lau et al. 1995; González et al. 1997; Marin et al. 2010; Kim et al. 2010). The simulation results (including CO_2 fixation) will change with the conversion efficiency of the limiting reactants.

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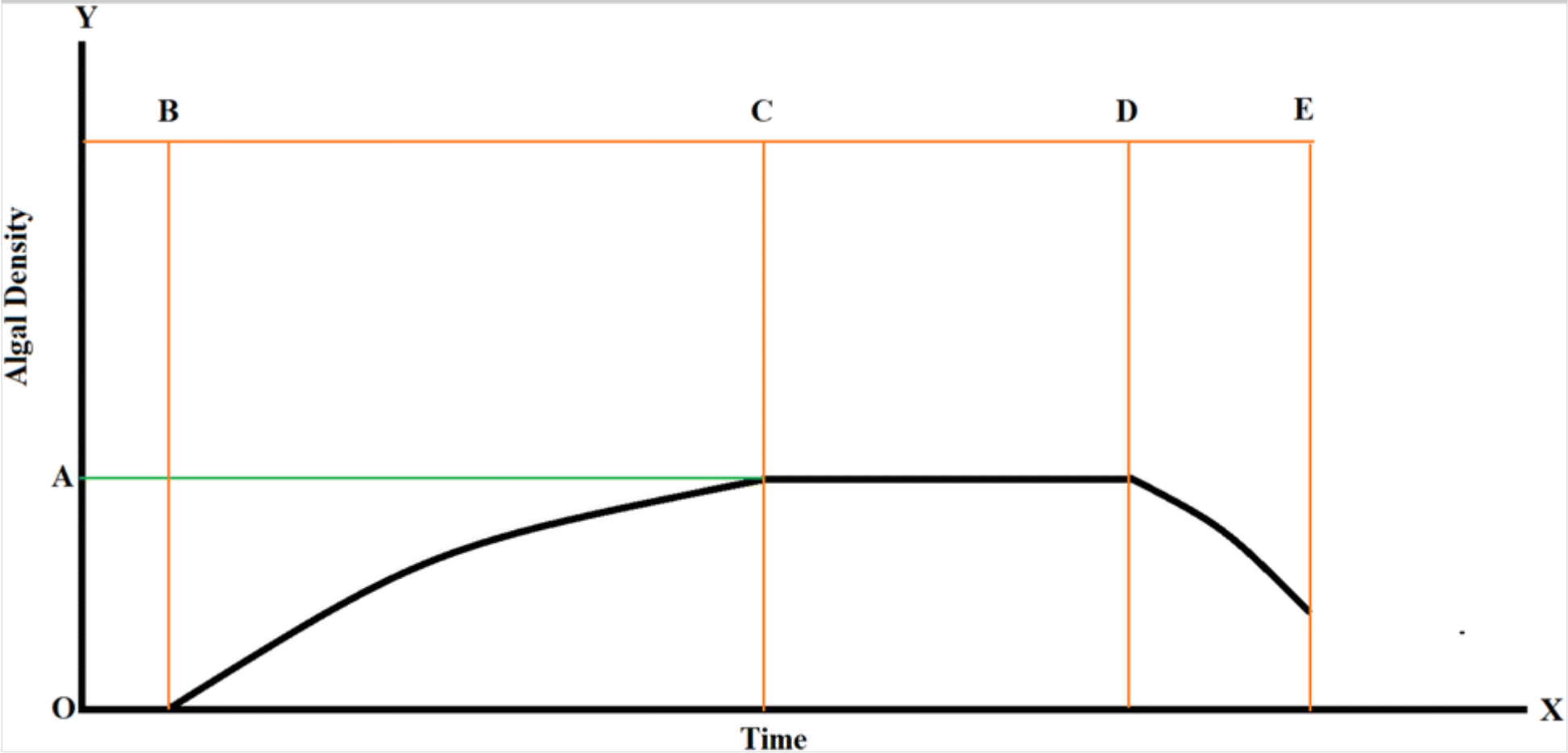
Moreover, in the simulation, bioremediation stops when the algal density reaches a maximum (indicated as C in Fig. 5). The simulation results do not show the algal growth pattern, which includes the lag phase, growth phase, stationary phase, and death phase, as shown in Fig. 5. However, in practice, algal cell replication continues after reaching the maximum density indicating continuous nutrient uptake. Many laboratory experiments continued cultivation after achieving the highest biomass density, which is a reason the experimental results showed a higher bioremediation efficiency than our simulation.

Fig. 5

Schematic growth trend of microalgae (OB—lag phase, BC—growth phase, CD—stationary phase, DE—death phase; OA—maximum algal density)



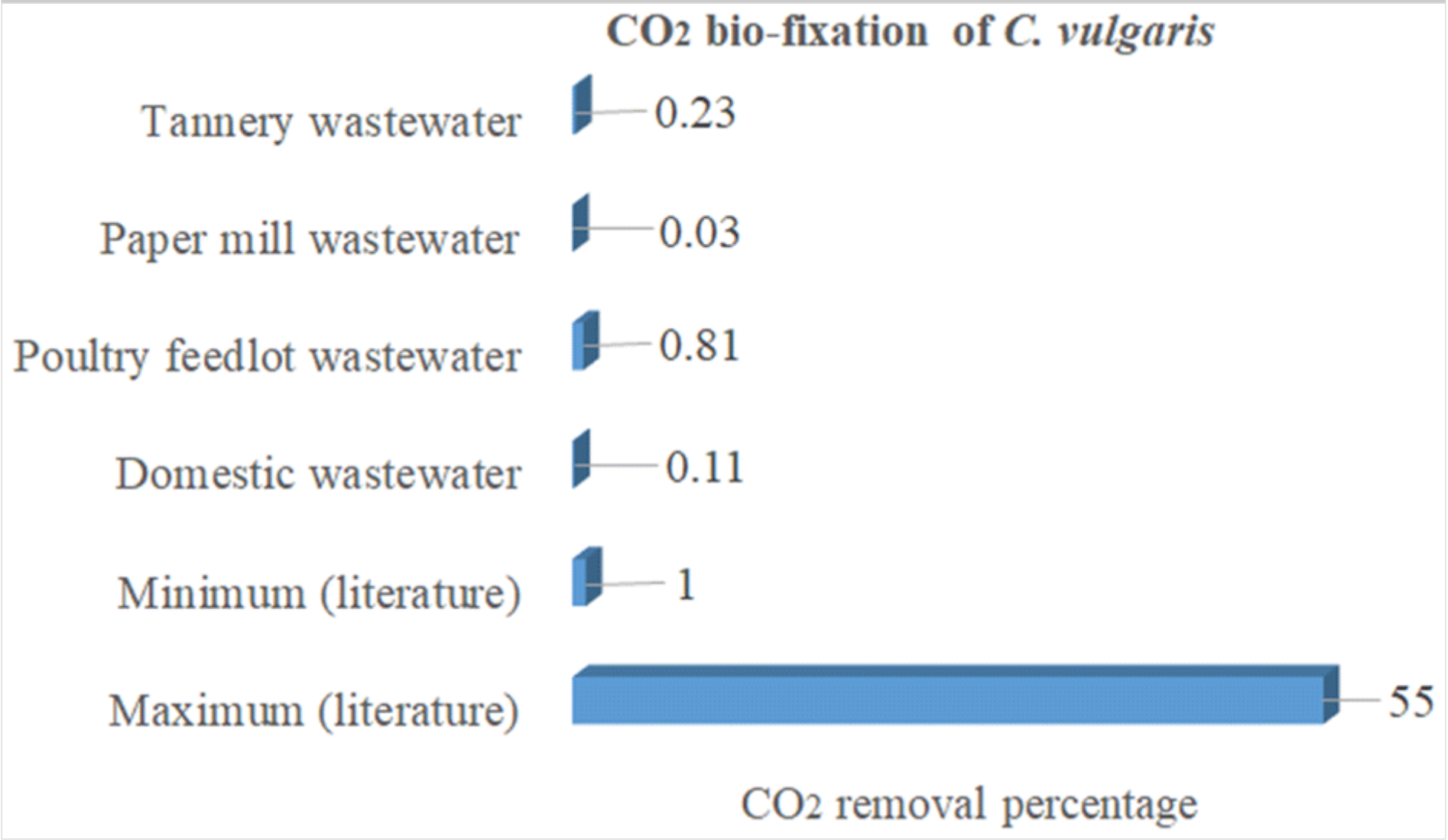
5.3. CO_2 biofixation

The CO_2 fixation efficiency found in the simulation was very low. One report suggests a negative relationship between CO_2 concentration and CO_2 biofixation with microalgae: the maximum CO_2 biofixation efficiency with *C. vulgaris* was 55% with a 0.25% concentration of CO_2. However, with a 3% CO_2 concentration, the biofixation rate was minimal, approximately 1% (Cheng et al. 2006), even though this value was higher than our result (Fig. 6). In this study, we

considered only the CO_2 removal percentage, not the CO_2 removal rate. Singh et al. (2015) reported that when the percentage of CO_2 increases, the rate of CO_2 fixation also increases.

Fig. 6

Comparison of CO_2 biofixation capacity of *C. vulgaris* between values obtained in this study and found in the literature



6. Conclusion

This article underlines the characteristics of the design steps/parameters of different types of batch algal cultivation processes and their ranking. In designs for various algal cultivation conditions, we recommended specific sequences of steps. These designs will be especially helpful to achieve the optimum growth of an algal species that has not undergone experimentation to study the optimum values of the parameters. Fertilizers and chemicals are selected for freshwater systems, where optimum nutrient ratios, such as a N/P ratio of 10:1, can be easily implemented, which is not possible for wastewater. However, wastewater from any source can be used to provide enough N and P. CO_2 can also be employed with freshwater. Biogas, producer gas, and even natural gas can also be used as sources of C because unwanted CO_2, which accounts for 30–60% of these energy sources, needs to be removed to increase the energy content per unit. The integration of an algal cultivation system can be an innovative approach to remove CO_2. Based on the availability of raw material and the suitability, the implementation of any combination serving the purpose effectively is possible.

Because of the lack of empirical constants for *C. vulgaris*, we used simple formulas from Monod's model. Additionally, Monod's model and SuperPro Designer do not take into account pH; for instance, both of them show the same result at pH 6.0 and pH 9.5, which is highly unlikely. Similarly, light intensity cannot be adjusted in SuperPro Designer. Simulation of the two hybrid conditions mentioned in Table 1—indoor pond and outdoor PBR—was not possible for these reasons because SuperPro Designer only allows simulation with open ponds and PBRs. While the algal growth and bioremediation results support almost 100% of the literature data, the calculated CO_2 biofixation was only 15% of the highest biofixation found in the literature. Therefore, we conclude that Monod's model and SuperPro Designer software can be considered for algal growth and bioremediation but are not recommended for CO_2 biofixation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

7. Appendix

Maximum specific growth rates of the limiting nutrients:

For light intensity, $\mu_{mI} = 0.96\ day^{-1}$ (Sasi et al. 2011)

For nitrogen, $\mu_{mN} = 0.225\ day^{-1}$ (Aslan and Kapdan 2006)

For phosphorus, $\mu_{mP} = 0.07\ day^{-1}$ (Aslan and Kapdan 2006)

For carbon, $\mu_{mC} = 0.168\ day^{-1}$ (Novak and Brune 1985)

Half saturation constants of the limiting nutrients:

For light intensity, $K_I = 12.852\ \mu\ mol\ m^{-2}\ s^{-1}$ (Sasi et al. 2011)

For nitrogen, $K_N = 31.5\ mg\ l^{-1}$ (Aslan and Kapdan 2006)

For phosphorus, $K_P = 10.5\ mg\ l^{-1}$ (Aslan and Kapdan 2006)

For carbon, $K_C = 0.26\ mg\ l^{-1}$ (Novak and Brune 1985)

The equation of light intensity is applicable for light intensity 0–550 μ mol $m^{-2}\ s^{-1}$ (Chae et al. 2006). Irradiance units were converted to μmol $m^{-2}\ s^{-1}$ according to the guidelines of Thimijan and Heins (1983) (Thimijan and Heins 1983).

$V_m = 24.465\ l\ mol^{-1}$ (at 25 °C and 1 atm molar volume of the gas).

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