Experimental Investigation on the Integration of Raceway Pond and Airlift Pump for Microalgal Cultivation

Afshin Ghorbani*‡, Mohammad Reza Rahimpour*, Younes Ghasemi**, ***, ****, Sona Raeissi*

*Department of Chemical Engineering, School of Chemical, Petroleum and Gas Engineering, Shiraz University, Shiraz, Iran

**Department of Pharmaceutical Biotechnology, Faculty of Pharmacy, Shiraz University of Medical Sciences, Shiraz, Iran

***Department of Medical Biotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran

****Pharmaceutical Science Research Centre, Shiraz University of Medical Science, Shiraz, Iran

(afshinghorbani@yahoo.com, rahimpor@shirazu.ac.ir, ghasemiy@sums.ac.ir, raeissi@shirazu.ac.ir)

‡ Corresponding Author; Afshin Ghorbani, Department of Chemical Engineering, School of Chemical, Petroleum and Gas Engineering, Shiraz University, Shiraz, Iran, Tel: +98 917 106 8034, Fax: +98 713 613 3673, afshinghorbani@yahoo.com

Received: 10.02.2018 Accepted:18.03.2018

Abstract- This work analyzed an integration of raceway pond and airlift pump (RWPAP) for microalgae cultivation. Therefore, the reactor was evaluated under various configurations of liquid depth in the raceway reactor, air flow rates, two riser airlift pump diameter and two nozzle hole diameter. The minimum air flow rate necessary for circulating medium in the RWPAP reactor in addition to the liquid velocity in the reactor was investigated. These parameters as well as the power consumption were determined in order to achieve the maximum efficiency and effectiveness configuration. The maximum effectiveness configuration of the RWPAP system was achieved at the water depth 40 cm, air flow rate 0.83 L min^{-1}, injector hole diameter 0.5 mm and tube diameter 0.75 inch that produced the maximum ratio velocity to power consumption with near one tenth of power consumption of the maximum efficiency configuration. At these configurations, the microalga *Dunaliella Salina* was cultivated in the natural culture medium from the Maharlu Salt Lake, southeast of Shiraz, Iran in order to achieve commercialization and reduce cultivation cost and the results showed that the effectiveness configuration had better biomass productivity, CO_2 utilization efficiency, power consumption and water evaporation rate compared to another configuration. The effectiveness configurations gave comparable batch biomass productivity (0.096 g L^{-1} day^{-1}) and 25.37% CO_2 utilization efficiency, but around five-times higher biomass productivity per unit power input (2.21 g W^{-1} day^{-1}) than reported for the modified airlift reactors. Furthermore, the β-carotene content and composition of fatty acids were evaluated.

Keywords Microalgal cultivation, an integration of raceway pond and airlift pump, CO_2 utilization efficiency, *Dunaliella Salina*, β-carotene, fatty acids composition.

1. Introduction

Open raceway ponds for large scale commercial microalgae cultivation has been accepted as the dominant system compared to closed photobioreactors due to small capital investment, operating cost and easy scale-up [1-7]. Despite this, current economic evaluations of microalgal cultivation pointed out the open raceway for biodiesel production in the form of traditional design may not improve energy efficiency and reduce costs effectively due to low aerial biomass productivity per unit energy input [8]. Algal cultivation costs which depend on the mixing system employed, accounts for nearly 28% of the total production cost [9]. The general design of raceway ponds containing shallow channels (0.2-0.4 m deep) [10] with one or more paddle-wheels and carbonation sumps have been recognized as an energy-intensive and poor mixing system for light and carbon utilization efficiency [11-14]. In order to improve carbon utilization efficiency, different configurations such as sumps with a baffle have been proposed to increase the gas/liquid contact, the rate of mass transfer and provide sufficient turbulence. Whereas recent studies indicated that in these modified configurations of the sump compared to without a baffle in the sump, the power requirement in the raceway ponds is increased by nearly 6 folds at the same flow velocity [15]. Therefore, mixing and low areal productivity (2-8 times lower compared to photobioreactors) are still the major concerns and challenges in raceway reactor ponds (RWPs) [16, 17].

The most important factor affecting biomass productivity is mixing, especially vertical mixing causes movements of the medium from the dark zone (bottom) to the light zone (upper layer). In fact, vertical mixing influences light and carbon utilization efficiency, gas/liquid mass transfer, efficient light/dark cycle and accessibility of the nutrient for algal cells. Vertical mixing in RWPs is very poor compared to the photobioreactor [18]. In a traditional RWPs, appropriate mixing occurs mainly near paddle-wheels, 180° bends and sumps except long straight channel of RWPs, especially in the large scale cultivation. Mendoza et al. compared mass transfer coefficients at different sections of the raceway pond and reported 164.50, 63.66, 0.87 and 0.94 h^{-1} for paddle wheel, sump, straight and curved channel sections respectively [18, 19].

Consequently, these limitations of raceway reactors have encouraged the use of photobioreactors such as airlift reactors with volumetric algal productivities 0.2-3.8 g L^{-1} day^{-1} compared with 0.12-0.32 g L^{-1} day^{-1} in raceway ponds [20]. In this regard, Ketheesan et al. proposed a new configuration of the small scale raceway reactor in the laboratory equipped with two down comers, risers and spargers at the bottom of the riser side. Regardless of obtaining batch maximum volumetric productivity of 0.085 dry gL^{-1} day^{-1} and the maximum CO_2 utilization efficiency of 33%, their design is not applicable in the large scale-up microalgae raceway ponds. However, the use of airlift system in their configuration enhances utilization efficiency [21]. Despite many research about airlift bioreactors, the efficient use of airlift system in the RWPs, has not been widely studied. Therefore, cost-effective reactor, which combines raceway pond with airlift system needs to be designed. From the viewpoint of this research, airlift pumps can use in a raceway reactor in combination of paddle-wheel, especially in the straight channel and after the bends to recirculate microalgae from the bottom in order to improve vertical mixing and even velocity in the raceway ponds.

Mixing by airlift tube in RWPs is superior to the different modifications of sumps in no head loss and rotation of liquid from the bottom (dark zone) into the surface (light zone) which cause improving light utilization efficiency and productivity. However, this system has advantages of simple mechanic, little maintenance required and even eliminating the energy consumption of paddle wheel by using waste flue gases from industrial processes.

Moreover, waste heat of flue gases could be used to control the temperature of the system in cold seasons [22]. Furthermore, this system can be utilized in the case of fragile microalgae cells to shear stress [23, 24] due to the absence of moving parts and generation gentle mixing. Hence, in this research, the proposed RWPAP reactor (an integration of raceway pond and airlift pump) by Afshin Ghorbani et al. was modelled [25]. The behaviour of the medium in the entire system under various configurations of the main variables which influence the performance of the system was analysed; main variables such as liquid depth in the raceway reactor, air flow rates, the riser diameter of airlift pump and nozzle hole diameter.

Thus, this reactor was operated at three liquid depths (30, 35 and 40 cm), three air flow rates (2, 4 and 6 L min^{-1}), two riser diameter (0.75 and 1 inch) and two nozzle hole diameter (0.5 and 0.7 mm). The depth higher than the mentioned range in commercial production is limited due to restricted sunlight penetration. These two tubes diameters were chosen due to circulating medium in the RWPAP reactor with low mechanical power consumption. At the beginning, the minimum air flow rate necessary for circulating medium in the RWPAP reactor in function of the liquid depth was investigated. These critical parameters in addition to the power consumption were determined in order to achieve the optimal configuration of depth, air flow rates, riser diameter and nozzle hole diameter for operating RWPAP reactor from the viewpoint of the efficiency and effectiveness. Afterward the microalga *Dunaliella Salina* isolated from the Maharlu Salt Lake, southeast of Shiraz, Iran was cultivated in the maximum efficiency and effectiveness configuration of RWPAP reactor.

In this research, for microalgal cultivation, the Maharlu Salt Lake medium was used in order to achieve commercialization and decrease cultivation cost. Despite much research on Dunaliella Salina isolated from the Maharlu Salt Lake [26-29], the natural culture medium from the mentioned lake for cultivation has not been yet utilized. Cynthia F. M. et al. analyzed energy and water requirement for large scale microalgal cultivation and reported that in the current technologies, energy needed to manage the water alone was roughly double times greater than energy output in the form of algal biomass and seven times more than energy output in the form of biodiesel [30].

Therefore, it is critical to assess the water management requirements for understanding the energy balance of any microalgae cultivation system. In this regard, water management, especially the water loss due to evaporation as the major challenge and concern in open pond systems of algae were addressed. Moreover, CO_2 utilization efficiency of the maximum effectiveness and efficiency configuration of RWPAP reactor was investigated. In this work, in order to better comparison, two methods were applied to measure CO2 utilization efficiency. At First method, fixation rate and utilization efficiency of CO_2 were estimated from algal biomass productivity (g L^{-1} day^{-1}) [21, 31, 32]. In the following, another method was applied by the acid-base neutralization reaction between NaOH and the acid carbonic [33, 34].

Consequently, the best configuration according to biomass productivity, CO_2 utilization efficiency, power consumption and water evaporation rate was determined. Furthermore, the β-carotene content and composition of fatty acids of the isolated microalgae which could produce valuable pharmaceutical and industrial product for human or animal food was studied.

2. Methods

2.1. The integration of raceway pond and airlift pump (RWPAP) configuration

The RWPAP reactor, is shown schematically in "Fig.1". The reactor consists of two sections; a raceway and airlift tube. The reactor was constructed out of glass; width of 15 cm, length of 30 cm and depth of 45cm.

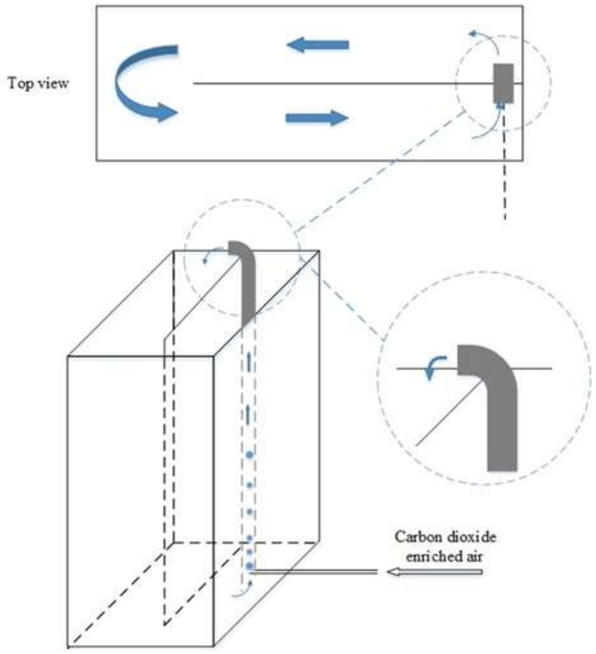

Fig. 1. Schematic of raceway pond integrated with airlift pump.

The raceway comprises a middle wall, allowing liquid medium passing just from one side. The airlift tube was located at the end of closed side of middle wall and fabricated out of diplexglass pipe with two sizes of 0.75 and 1 inch inner diameter and total length 43 cm with its foot end 2 cm above the bottom. CO_2 enriched air was sparged from the bottom of the tube to generate bubbles. These bubbles raise the medium in the tube due to decrease in the density of the air-medium mixture in the tube and causes circulating the medium around the raceway as illustrated in the "Fig.1".

Air is supplied to the airlift tube from an air pump at the pressure of 1.045 bar. The air is injected to the sparger after passing a rotameter used to measure air flow rates. The spargers consist of two configurations with the same area of 10 mm^2; 51 and 26 small holes of 0.5 and 0.7 mm diameter, respectively. The end of the riser is connected to a calibrated cylinder used as a flow meter. Clean water was used for determining the fluid dynamic parameters of RWPAP reactor. Since the lifted medium was forced to cross from one side of the middle wall, then the average liquid velocity in the reactor was calculated by dividing the liquid medium volumetric flow rate by the cross-sectional area of the reactor. Clean water was used for determining these fluid dynamic parameters of RWPAP reactor.

2.2. Growth of Dunaliella Salina in the RWPAP reactor

2.2.1. Culture medium and reactor operation

The microalga *Dunaliella Salina* was isolated from the Maharlu Salt Lake, 30 km southeast of Shiraz, Iran. The strain was identified by Bacteriological and botanical approaches [35] and added to Microalgal Culture Collection of Shiraz University of Medical Sciences (MCCS). In order to reduce cultivation cost, the Maharlu Salt Lake medium was used as the medium for microalgae growth in the reactors.

Maharlu Salt Lake medium composed of (milligram per liter): HCO_3^- (73.20); Cl^- (70112.50); SO_4^{2-} (480.00); Ca^{2+} (375.00); Mg^{2+} (225.00); Na^+ (44835.05); K^+ (122.85); NO_3^- (1002.40); $H_2PO_4^-$ (35.00); PO_4^{3-} (0.33). Two fluorescent tubes of 36W were utilized for illumination with an average photosynthetically active radiation (PAR) of 72 μmol m^{-2} s^{-1} measured at the surface of RWPAP reactor. During growth, the temperature was kept at 30°C. CO_2 with injection flow rate of 0.4 L min^{-1} was injected into each reactor and mixed with ambient air before releasing into the risers of the reactors. When CO_2 was injected, the pH decreases. Therefore, the air without CO_2 was injected for increasing the PH. Every two hours, five minutes CO_2 was injected to maintain PH suitable for cultivation.

2.2.2. Sampling and analysis

The growth of microalgae was determined by cell number and optical density each two days during the cultivation period. Cell number was performed using a Neubauer hemocytometer and a light microscope for 1 ml of algal suspension harvested. Optical density was measured at a wavelength of 735 nm by UV/Visible spectrophotometer. The biomass dry weight was determined after centrifuging at 4000 RPM for 5 minutes, rinsing three times with de-ionized water for removing salt and other media chemicals and drying overnight by an oven at 60 ± 2 °C [36]. Dry weight of the algal suspension during cultivation was correlated by OD and cell number.

2.2.3. Growth performance

Biomass productivity, P_b (g L^{-1} day^{-1}) and specific growth rate, μ (day^{-1}) were estimated from the following relationships [37, 38]:

$$\mu = \ln(C_{Bf} - C_{B0})/\Delta t \quad (1)$$

$$P_b = (C_{Bf} - C_{B0})/\Delta t \quad (2)$$

Where C_{Bf} and C_{B0} were the final and initial biomass concentrations (g L^{-1}) in during cultivation, Δt (day).

2.2.4. Extraction of total lipids and Esterification of fatty acids

After reaching stationary growth phase, the obtained algal pellets (0.5 g) from harvesting, centrifuging and drying by freeze-drier were boiled for 2 min in 5 ml of isopropanol. Subsequently it was dried under nitrogen gas and homogenized in chloroform-methanol (1:2 v/v) and added about 0.015 Butylated hydroxytoluene to the system. In order to cell debris, the mixture was centrifuged for 5 min at 2000 rpm. The obtained supernatant was shaken and separated in a funnel after adding 0.8 ml water, 5 ml chloroform and 5 ml of 0.88% potassium chloride solution. The lipid extract was collected from solvent phase and concentrated under nitrogen gas. Then it was dissolved in 3 mL of methanol in the presence of catalytic amount of sulphuric acid [39, 40]. After washing twice with 4 mL of saturated sodium hydrogen carbonate solution and drying over anhydrous sodium sulphate, the remained oily substance was injected in Hewlett–Packard 6890 GC/MS for analysis of methyl esterification of fatty acids. It was equipped and programmed with HP-5 M capillary column (phenyl methyl siloxan, 25 m × 0.25 mm, Palo Alto, CA, USA), helium carrier gas with the flow rate of 1.2 mL/min and oven temperature 265°C for 10 min.

2.2.5. β-carotene extraction

The β-carotene was determined spectrophotometrically at 450 nm. Afterward centrifuging 1 ml of *Dunaliella salina* suspension for 10 min in 3000 rpm, the supernatant was mixed with 3 mL n-hexane-ethanol (1:2 v/v) solution. After vortexing and again centrifuging, the upper phase (n-hexane phase) was used for measuring β-carotene content by a UV/Visible spectrophotometer (PG instrument Ltd.) at Shiraz University of Medical Sciences. The amount of β-carotene was calculated as following equation [27]:

$$\beta\text{-carotene content } (\mu g/ml) = 25.2 \times A_{450} \quad (3)$$

The β-carotene content in this research was presented as mg g^{-1} by knowing biomass content.

2.2.6. CO_2 fixation performance

Some researchers estimated fixation rate of CO_2 per unit culture volume, F_{CO2} (g L^{-1} d^{-1}) from the equation between biomass productivity, P_b (g L^{-1} day^{-1}), carbon content, C_{carbon} (g CO_2 g $biomass^{-1}$), molar mass of carbon, MW_C and dioxide carbon, MW_{CO2} as indicated in below equation [21, 31, 32]:

$$FCO_2 = Pb \times Ccarbon \times (MW_{CO2}/ MW_C) \quad (4)$$

On the other hand, Tang et al. analyzed elemental carbon of the two microalgal cells cultivated under the different carbon dioxide concentration from 0.03 to 50% and reported their carbon content did not change significantly and were about 50%. Other researchers such as Balachandran Ketheesan et al. and Ho et al. in estimating carbon dioxide fixation rate considered 50% for carbon content in the dry biomass. Therefore, the CO_2 fixation rate equation was summarized into the following equation [21, 32]:

$$F_{CO2} = 1.833\ P_b \quad (5)$$

Molar mass of carbon and carbon dioxide are 12 and 44, respectively. Accordingly utilization efficiency of CO_2, η_{CO2} (%), can be estimated as:

$$\eta_{CO2} = (1.833\ P_b/Q_{CO2}) \times 100 \quad (6)$$

Where Q_{CO2} (g CO_2 L^{-1} day^{-1}) was carbon dioxide flow rate supplied to the unit volume of RWPAP reactors. Utilization efficiency of CO_2 determined from this way which utilized by many researchers could introduce uncontrolled variables such as those related to photosynthesis into the measurements [41]. Therefore, in this research in order to better decision, CO_2 utilization efficiency was measured from two independent methods. Ron Putt et al. calculated CO_2 mass-transfer efficiency, $E_{CO2\ transfer}$ (%) based upon a stoichiometric relationship by utilizing the acid-base reaction between NaOH and acid carbonic at the specific PH range such as 7.5-9.5 and determining the moles of NaOH needed to increase the pH of the reactor medium which decreased from CO_2 adding into the reactor. Two moles of NaOH in the water would neutralize one mole of CO_2. The amount of carbon dioxide, M_{CO2} sodium hydroxide, M_{NaOH} and consequently the efficiency of carbon dioxide transfer can be calculated from following equation [34]:

$$M_{CO2} = (\tau \times V_{CO2})/V_m \quad (7)$$

$$M_{NaOH} = V_B \times \rho \times C_{NaOH} \quad (8)$$

$$E_{CO2\ transfer} = (M_{NaOH}/2M_{CO2}) \times 100 \quad (9)$$

Where V_{CO2} was the carbon dioxide flow rate (0.4 L min^{-1}), V_B was the volume solution of NaOH for increasing the pH from 7.5 to 9.5, τ was the sparging time of carbon dioxide (min), ρ was the medium density (1.1 g mL^{-1}), C_{NaOH} was the molar concentration of NaOH and V_m was carbon dioxide molar volume at atmospheric pressure and 25 °C temperature (24.465 L mol^{-1}).

3. Results and Discussion

The airlift performance depends upon several conditional and geometrical parameters. The main parameter for the description of airlift system operation is the submergence ratio determined from dividing the submerged length by the riser length. Since the total riser tube length in the system is constant, then we investigate only the effect of the submerged length or medium depth. In the following, this paper investigates the influence of several conditional and geometrical parameters on the efficiency and effectiveness of the RWPAP reactor such as riser tube diameter (0.75 and 1 inch), medium depth (30, 35 and 40 cm), air injector hole diameter (0.5 and 0.7) and air flow rate ranging from 0.83 to 8.33 L min^{-1}.

3.1. Performance of RWPAP reactor

In order to achieve a liquid medium circulation in RWPAP system, i.e. to raise medium from the tube, a minimum air flow rate was needed. Below this amount of air flow rate, medium in RWPAP system was not circulated.

The minimum air flow rate depended upon the diameter of the riser and water depth. “Figure 2” shows the minimum air flow required in RWPAP versus the water depth.

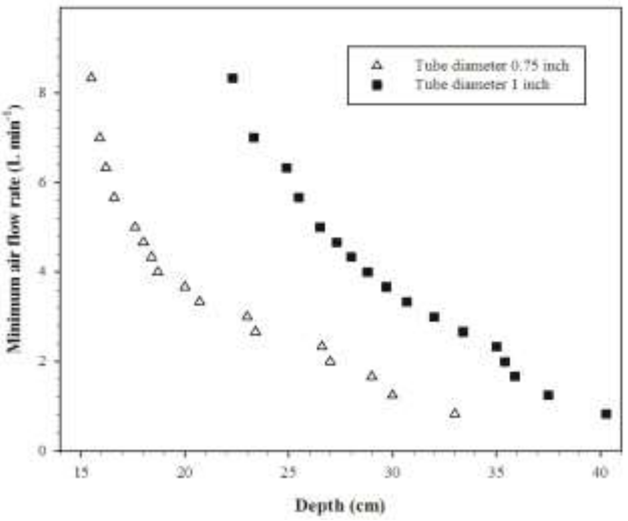

Fig. 2. Minimum air flow required in RWPAP versus water depth

It can be seen from the “Fig.2” that the minimum air flow rate decreased with increasing water depth. Moreover, in order to lift up the water at low depth, more mechanical work leading to more air flow rate was needed. From the other hand, increasing air flow rate leads to change flow pattern and has the reverse effect on fixation rate and system efficiency. Therefore, the small tube diameter should be used for low medium depth. In “Fig.3” the water flow rate (Q_w) was plotted for different water depth versus the air flow rate (Q_a). The gas: liquid ratio (G/L) was shown in these figures for understanding the importance of air flow rate of the input energy to raise the medium.

The results point out a common pattern of variation, first a rapid increase and then at the higher air flow rates, water flow rate tends to increase slowly and become constant or even decrease due to strongly unstable flow pattern in the riser. The G/L ratio was higher at 30 cm and especially for tube diameter 1 inch compare to 35 and 40 cm which presented high initial input energy requirement for raising the water. In addition the results demonstrate that the riser tube diameter and air injector hole diameter have some effect on the airlift performance. Increase in tube diameter has the reverse effect on water flow rate at water depth 30 and 35 cm except for the higher air flow rate at the water depth 35 cm.

On the contrary, a similar behavior was observed at the water depth 40 cm until the air flow rate reaches 3 L min^{-1}. After this air flow rate, increase in tube diameter causes water flow rate increasing, even 35%. Moreover, comparisons between these figures reveals that an increase in the water depth results increasing the water flow rate. This increasing are expected due to the difference in the bulk masses of water in the airlift riser. Observing the curves reveals that water flow rate increases with an asymptotic value after a stable slope at lower air flow. In contrary to the water depth, an increase in the tube diameter decreases this asymptotic value. However, the air injector hole diameter has no definite effect on this asymptotic value.

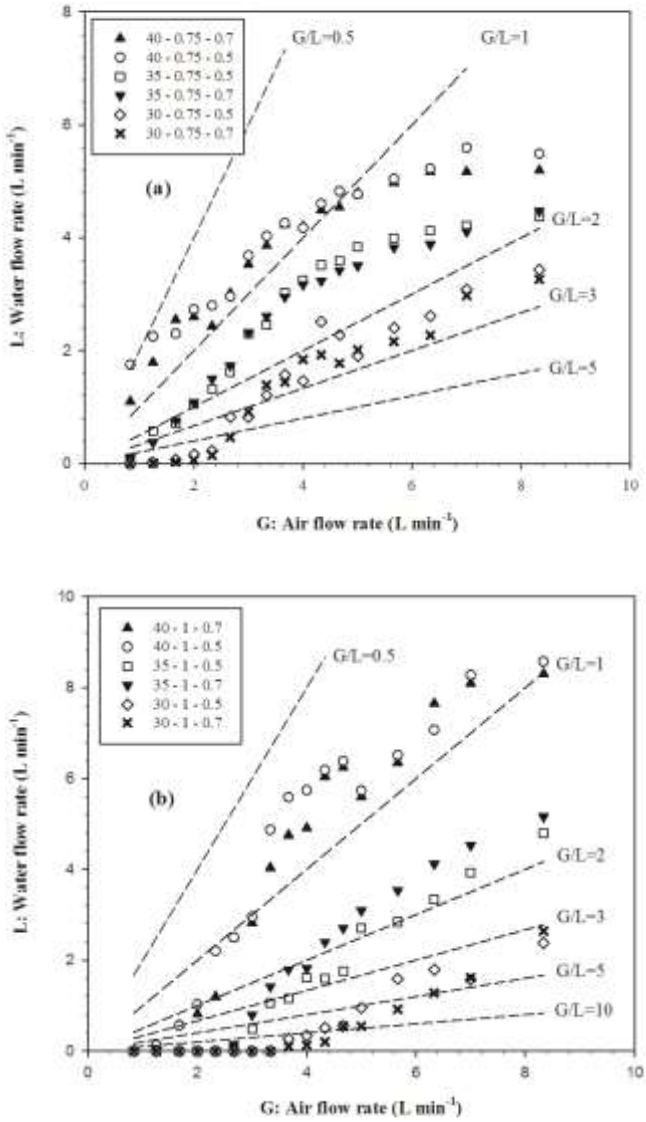

Fig. 3. Effect of the water depth for the tube diameter 0.75 inch (a) and 1 inch (b)

3.2. Power consumption, efficiency and effectiveness

Mechanical power consumption of the airlift section in RWPAP system can be defined as the input energy for lifting up the water to the height of unaerated liquid and calculated as the following equation.

$$P_m = Q'_g R' T \ln(1+\rho_w g H_l/P_{air}) \quad (10)$$

Where P_m is the mechanical power consumption (W), H_l is the unaerated liquid height in riser (m), P_{air} is atmospheric pressure (Pa), R' is universal gas constant (8314 L Pa mol^{-1} K^{-1}), T is temperature (K), Q'_g is molar flow rate of gas (kmol/s), ρ_w is the water density (kg m^{-3}), and g the gravitational acceleration (m^2 s^{-1}). “Figure 4” shows the power consumed for the corresponding raceway velocity in the RWPAP system.

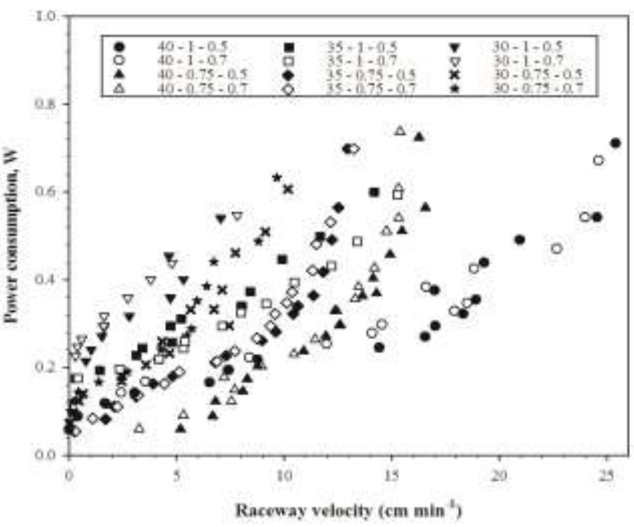

Fig. 4. Power consumed for the corresponding raceway velocity in the RWPAP system

The results indicated that the high velocity needed more power consumption. In contrary to the paddlewheel raceway system, as the water depth increased the power consumption decreased. As can be seen in this figure, for all raceway velocities, the minimum power consumption was related to the water depth 40 cm, especially the injector hole diameter 0.5 mm. It means that with the same power consumption, higher water depth can produce more raceway velocity. For example, with the near 0.4 w power consumption, the water depth 30, 35 and 40 cm can produce raceway velocity of 7.29, 10.46 and 17.88 cm min^{-1}. The efficiency parameter of the airlift section in RWPAP system, η, can be described as the ratio of the power needed for lifting up the water to the height difference between unaerated liquid and water depth, H_d to the input energy. Under this definition, airlift efficiency equation becomes:

$$\eta = (\rho_w g Q_w H_d)/(Q'_g R' T \ln(1+\rho_w g H_u/P_{air})) \quad (11)$$

Where H_d is the height difference between unaerated liquid and water depth and Q_w is the flow rate of water lifted (m^3 s^{-1}). “Figure 5” presented experimental results of airlift efficiency versus the air flow rate for all configurations. This figure indicated that as the air flow rate increased, the airlift efficiency was enhanced until attaining a value beyond which the efficiency decreased and in some cases then increased. This behavior was due to the operation of airlift in the different flow regimes.

The figure indicated that in the air flow rates and the water depth mentioned, tube diameter 0.75 inch was more efficient than 1 inch. As can be seen in this figure, in contrary to tube diameter, there was no better injector hole diameter for all the air flow rates, although at a specified air flow rate and water depth, the highest efficiency could be found. In addition to efficiency, effectiveness, Q_w/Q_g is the most important dimensionless parameter for the performance of airlift pumps without considering loss through the injector, as it describes the volume of air provided to lift a specified volume of water. This figure indicated that at low air flow rates, η was an increasing function of air flow rate though not a linear one.

Acquiring air and water flow rate corresponding to the maximum efficiency, Q_{gmax} and Q_{wmax} was important for the current system.

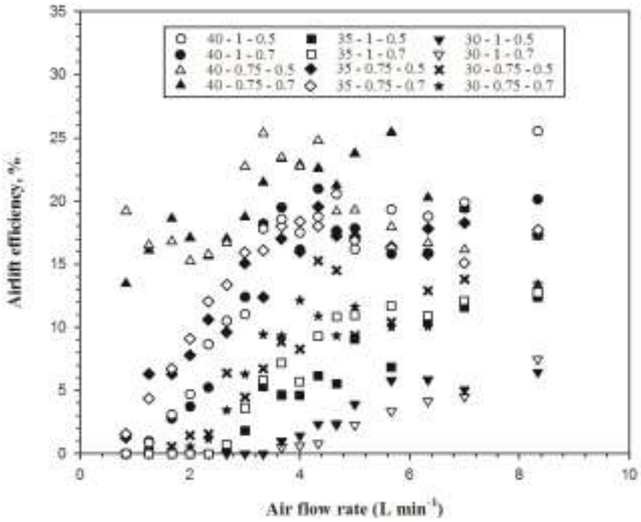

Fig. 5. Airlift efficiency versus air flow rate for all configurations

As can be seen in the figures, the maximum airlift efficiency was not necessarily consistent with the maximum airlift effectiveness and maximum water flow rate. This may be ascribed to the lack of the input power in the effectiveness relation. As mentioned, in some conditions, high air flow rate produced more water flow rate, but with a much lower effectiveness. It should be noticed that, although at the same water depth, riser diameter 0.75 inch had a greater maximum efficiency than riser diameter 1 inch, their corresponding water flow rates were two times lower at the water depth 40 cm. As expected, injector hole diameter had not significant influence on maximum efficiency. Concisely, the knowledge of the maximum efficiency and effectiveness and the consistent air and water flow rate besides microalgae growth data were important to achieve optimal operation of RWPAP reactor.

3.3. The optimum condition and configuration

The performance description of the reactor indicated that configuration of water depth, air flow rate, tube diameter and injector hole diameter all affected the behavior of the RWPAP system. It was interesting to evaluate the real potential of this reactor in cultivation of microalgae based on the optimum configuration. The maximum efficiency of the RWPAP system was achieved for the tube diameter 1 inch and injector hole diameter 0.5 mm at water depth 40 cm and air flow rate 8.33 L min^{-1}.

This configuration produced maximum raceway velocity of 25.4 cm/m with power consumption 0.7114 W. In regard to effectiveness, water depth 40 cm, injector hole diameter 0.5 mm and tube diameter 0.75 inch at the air flow rate 0.83 L min^{-1} was the optimum configuration of the RWPAP system. Furthermore this configuration produced the maximum ratio raceway velocity to power consumption with near one tenth of power consumption.

Therefore, these two configurations potentially denoted the optimum points in the efficient-energy of RWPAP systems.

3.4. Growth of Dunaliella Salina

In order to compare the maximum efficiency and effectiveness configuration of RWPAP system, *Dunaliella Salina* was cultured in this reactor at the water depth 40 cm and injector hole diameter 0.5 mm. One of this reactor as maximum effectiveness configuration had tube diameter and air flow rate 0.75 inch and 0.83 L min^{-1}, respectively. Another reactor, as maximum efficiency configuration had tube diameter and air flow rate 1 inch and 8.33 L min^{-1}, respectively. "Figure 6" illustrates algal growth observed in these reactors. In the following sections all aspects of these configurations in RWPAP reactor are compared with each other.

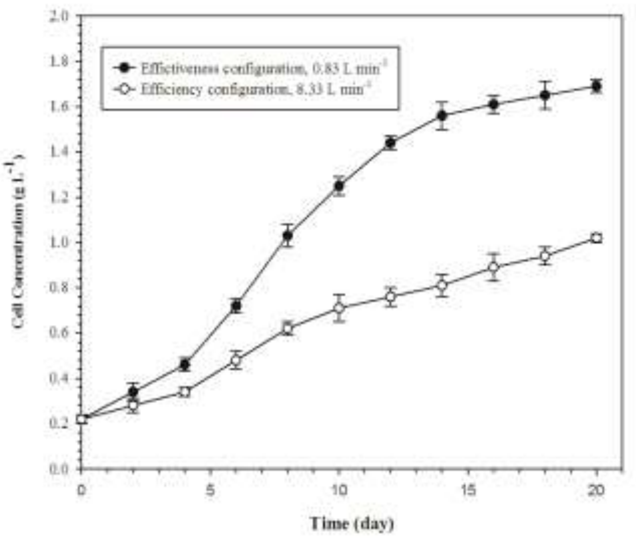

Fig. 6. Growth of Dunaliella Salina in the raceway pond integrated with airlift pump (RWPAP)

3.4.1. Growth performance, fatty acid identification and β-carotene content:

"Figure 6" indicated a comparison of growth curves for batch cultivation at the maximum efficiency and effectiveness configuration of RWPAP system. Approximately at the initial four days, the growth rate was same before attaining the exponential growth phase.

Afterwards a remarkable increase in biomass dry weight can be detected in the effectiveness configuration compared to that in the efficiency configuration. This behavior indicated that the low CO_2 utilization efficiency regardless of higher raceway velocity in the efficiency configuration compared to another configuration limited the growth. The maximum biomass productivity and specific growth rate observed after three weeks in the effectiveness configuration were 0.074 g L^{-1} day^{-1} and 0.166 day^{-1}, respectively. Furthermore, maximum biomass concentration (1.698 g L^{-1}) was attained at this configuration. Contrary to the effectiveness configuration, the efficiency configuration had lower biomass productivity (0.040 g L^{-1} day^{-1}) and specific growth rate (0.066 day^{-1}) in the same time. Moreover, the maximum biomass concentration (1.018 g L^{-1}) was noticed in this configuration. Specific growth rate and biomass productivity from the batch tests in two and three weeks were reported in "Table 1."

Table 1. Biomass productivity and specific growth rate for the batch experiments at the optimum configurations of RWPAP

Configuration	Specific growth rate (day^{-1})	Volumetric productivity ($g\ L^{-1}\ day^{-1}$)	
		In 14 days	In 21 days
Efficiency	0.066	0.042	0.040
Effectiveness	0.166	0.096	0.074

As can be seen from "Table 1." both configurations had higher values after two weeks compared to three weeks. Biomass productivity (0.096 g L^{-1} day^{-1}) of the maximum effectiveness configuration in two weeks was higher than biomass productivity of 0.085 g L^{-1} day^{-1} which was reported by Balachandran Ketheesan et al. in a 23-L airlift-driven raceway reactor comprised two risers and downcomers with 72 cm height in two weeks with Scenedesmus sp. and even biomass productivity of 0.085 dry g L^{-1} day^{-1} which was reported by Morais and Costa in a 2-L conical flask with Scenedesmus sp. in 20 days batch run [21, 42]. The volumetric productivity (g L^{-1} day^{-1}) in this study under batch mode culturing was compared with literature results in "Table 2."

Table 2. Biomass productivity in open raceways (batch mode) in literature vs. RWPAP (modified from [43])

References	Algae species	Productivity ($g\ L^{-1}\ day^{-1}$)
[44]	Chlorella sp.	0.026
[45]	Scenedesmus and Colostrum	0.086
[46]	Mixotrophic strains	0.057
[21]	Scenedesmus sp.	0.085
[47]	Spirulina sp.	0.060
[48]	Nannochloropsis sp.	0.208
This study	Dunaliella Salina	0.096

Regardless of differences in the conditions of the cultivation, such as light, CO_2 levels, and temperature, the result of RWPAP was comparable to or better than the studies listed in "Table 2." Fatty acids in the microalgae of *Dunaliella Salina* isolated from Maharlu Salt Lake was primarily esterified and then identified through GC/MS analysis. The systematic name, common name and the major fatty acid content of the microalgae are presented in the following table. The results indicated that *Dunaliella Salina* isolated from Maharlu Salt Lake have a considerable variety of polyunsaturated FAs which warrants a great market for the pharmaceutical and food industries.

The β-carotene content was determined spectrophotometrically from “Eq. (3)”.

Table 3. Fatty acid composition of Dunaliella Salina isolated from Maharlu Salt Lake [modified from 25]

Systematic name	Fatty acid content (% total)
Hexadecanoic acid	43.00
10,13-Octadecadienoic acid	9.60
9,12,15-Octadecatrienoic acid	10.98
Octadecanoic acid	23.72
Heneicosanoic acid	3.80
Docosanoic acid	8.90

After stationary phase stage of growth, the β-carotene content reached up to 10.53 and 9.87 mg g^{-1} for the maximum effectiveness and efficiency configuration of RWPAP reactor. As mentioned in Sec. 3.2, mechanical energy consumption per unit volume of the RWPAP reactor, P_m (W L^{-1}), was estimated from “Eq. (10)”. Total power input was calculated from mechanical energy input and light energy input P_l (W L^{-1}), which was estimated from the following equation:

$$P_l = 0.22\, I_L A_R/(1000\, V_R) \quad (12)$$

Where I_L is measured PAR value (µmol m^{-2} s^{-1}), A_R (m^2) and V_R (m^3) are cross section and volume of the RWPAP reactor.

Consequently, biomass productivity per unit power input (g W^{-1} day^{-1}) can be calculated as:

$$P_{B/b} = Pb/(P_m + P_l) \quad (13)$$

Therefore, mechanical power input per volume of effectiveness configuration (0.0037 W L^{-1}) was much lower than efficiency configuration (0.0445 W L^{-1}). Hence, biomass productivity per unit mechanical power input (without light energy) of 25.85 g W^{-1} day^{-1} after 14 days for the effectiveness configuration was much higher than efficiency configuration (0.951 g W^{-1} day^{-1}). Even biomass productivity per unit total power input for the effectiveness configuration (2.21 g W^{-1} day^{-1}) was better than literature as reported in “Table 4.” As can be seen in “Table 4”, Morais and Costa achieved biomass productivity per unit power input (0.51 g W^{-1} day^{-1}) by utilizing illumination of 12 h light/dark photoperiod and intermittent aeration of 15 min per hour [42]. The results of RWPAP reactor could be better and incomparable by utilizing sunlight and flue gases from industrial sources.

3.4.2: CO_2 fixation performance

As mentioned in Sec. 2.3.4, the carbon dioxide fixation rate was determined based on the “Eq. (6)”, and the results show that after 14 days the maximum CO_2 fixation rates of effectiveness and efficiency configuration were above 0.175 and 0.077 g L^{-1} day^{-1}, respectively. Considering biomass productivities in before a section, estimated CO_2 utilization efficiency of 23.8% and 10.5% were achieved in effectiveness and efficiency configuration, respectively. Ron Putt et al. analyzed CO_2 mass-transfer efficiency of system with free algae water [34]. Therefore, as described in Sec 2.3.4, the observed CO_2 mass transfer efficiency of effectiveness configuration of this method was 25.4% as compared to 8.2% in efficiency configuration at the alkaline pH range of 9.5 to 7.5.

CO_2 mass transfer efficiency for the effectiveness configuration was 17.1% higher than efficiency configuration as it took only 7.9 min for effectiveness configuration to decrease pH from 9.5 to 7.5, while the same results could only be attained in 24.6 min for efficiency configuration (“Table 5”). The results of two methods have a difference of 1.6% and 2.3 % for the effectiveness and efficiency configuration, respectively. According to the assumption of carbon content in the dry biomass (50%) in the first method, the results did not change significantly and could be acceptable.

Table 4. Biomass productivity per unit power input in literature vs. RWPBP (modified from [21])

References	Algae species	Reactor type	Cultivation	Volume (L)	Biomass productivity per unit volume (g L^{-1} day^{-1})	Biomass productivity per unit power (g W^{-1} day^{-1})
[32]	Scenedesmus obliquus	Bubble column	Batch	0.8	0.16	0.15
[42]	Chlorella kessleri	Bubble column	Batch	1.8	0.18	0.51
[42]	Chlorella vulgaris	Bubble column	Batch	1.8	0.14	0.40
[49]	Chlorella sp.	Tubular	Batch	0.5	0.34	0.16
[21]	Scenedesmus sp.	Airlift raceway	Batch	23.0	0.085	0.60
[50]	Nannochloropsis oculata	Bubble column	Batch	1.0	0.28	0.10
[51]	Nannochloropsis oculata	Bubble column	Semicontinuous	0.8	0.48	0.13
[51]	Chlorella sp. NCTU-2	Centric tube airlift	Semicontinuous	4.0	0.38	0.12
[21]	Scenedesmus sp.	Airlift raceway	Continuous	23.0	0.19	0.69
This study	Dunaliella salina	RWPBP	Batch	16.0	0.096	2.21

Table 5. CO_2 utilization efficiency for efficiency and effectiveness configuration of RWPAP

Configuration	NaOH added (moles)	CO_2 added time(min)-(moles)	CO_2 utilization efficiency (%)
Efficiency	0.0661	24.6 (0.402)	8.21
Effectiveness	0.0655	7.9 (.129)	25.37

Several researchers reported better results such as Chiu et al. [51] with CO_2 utilization efficiency of 35% by developing porous centric- tube airlift with biomass concentration of 2 g L-1 or Lv et al. with CO_2 utilization efficiency of 35% by using dead-end hollow fiber membrane sparger [52] or B. Ketheesan et al. with CO_2 utilization efficiency of 33% by constructing two risers and downcomers in the raceway with 72 cm height [21]. However, Ron Putt et al. reported CO_2 mass transfer efficiency of 83%, but they utilized carbonation column with a height of 3.0 m and a water pump for lifting the medium into the top of the carbonation column in order to prepare counter-current flow against the gas bubbles in the carbonation column [34]. It must be mentioned that CO_2 utilization efficiency of 25.37% in this research with mechanical power input per volume of 0.0037 W L^{-1} was better than some of literatures reported in "Table 6." which utilizing photobioreactor such as helical tubular, flat plate and bubble column. Ron Putt et al. do not report use of microalgae in their system and their result is not listed in mentioned table [34].

3.4.3 Water evaporation rate

In this section, the net amount of water loss from evaporation as the significant concern, especially in open ponds was observed. However, this amount can vary from site to site and particularly depends on weather conditions such as temperature, humidity, and wind velocity, but the evaporation rate in the mentioned configurations could be compared with each other. Both of these reactor had same height and illuminations. Thus injected, mixed air-carbon dioxide flow rate in the risers affected evaporation rate. Without mixed air-carbon dioxide flow rate and medium circulation, both reactors had a same evaporation rate 140 mL day^{-1}. While the average evaporation rate for the reactor with air flow rate injection of 0.83 L min^{-1} (maximum effectiveness configuration) and 8.33 L min^{-1} (maximum efficiency configuration) were 175 and 250 mL day^{-1}, respectively. These amounts of water loss were about 1.1 and 1.6 % of the reactor volume for the effectiveness and efficiency configuration, respectively. These results can be easily related to larger circulation of water and more turbulence of water surface in the maximum efficiency configuration compared to another configuration. It should be noted that current potential daily evaporation rates for the United States was estimated 13.3 m^3 per acre and was projected in the range of 908 to 2271 liter of evaporated water loss for each liter of algal oil produced [30, 54, 55]. "Figure 7" shows the important parameters to choose the best configuration for IARWP reactor. As shown in this figure, the effectiveness configuration has better CO_2 utilization efficiency and biomass productivity besides lower power input and water evaporation loss compared to the efficiency configuration.

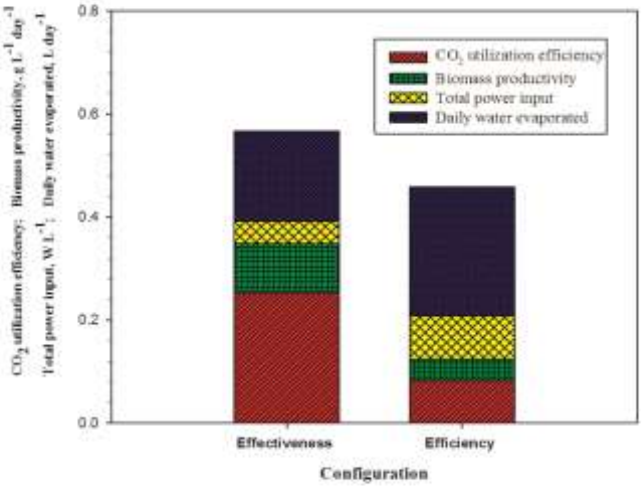

Fig. 7. Comparison of CO_2 utilization efficiency, biomass productivity, total power input and daily water evaporated for IARWP reactor.

4. Conclusion

An integration of raceway pond and airlift pump (RWPAP) was analyzed under various configurations of liquid depth in the raceway reactor, air flow rates, riser diameter of the airlift pump and nozzle hole diameter and the maximum efficiency and effectiveness configuration of the reactor were determined.

Table 6. CO_2 utilization efficiencies of microalgal bioreactors in literature vs. RWPBP (modified from [21])

References	Algae species	Reactor	Volume (L)	CO_2 utilization efficiency (%)
[53]	Scenedesmus + mixed culture	Helical tubular	9	2-3
[53]	Scenedesmus + mixed culture	Flat plate	10	8-10
[42]	Scenedesmus obliquus	Bubble column	4	5.87
[21]	Scenedesmus sp.	Airlift raceway	23	33
[51]	Chlorella sp. NCTU-2	Centric tube airlift	4	35
[52]	Chlorella vulgaris	Membrane sparged reactor	5	35
This study	Dunaliella Salina	RWPBP	16	25.37

In the reactor, the effectiveness configuration not only had better biomass productivity, CO_2 utilization efficiency and water evaporation loss, but also had significant biomass productivity per unit power input compared to the maximum efficiency configuration and even airlift photobioractors those reported in the literature.

Acknowledgments

Authors gratefully acknowledge School of Chemical, Petroleum and Gas Engineering, Shiraz University of Medical Sciences, Pharmaceutical Science Research Center for their continuous support to complete this research work.

Conflict of interest

The authors declare that there is no conflict of interest.

References

[1] Mukesh Kumar, M P Sharma, Gaurav Dwivedi, "Algae Oil as Future Energy Source in Indian Perspective", International Journal of Renewable Energy Research-IJRER, Vol.3, No.4, November 2013.

[2] V. Tachoth and A. Rose, "Site selection for large-scale algae cultivation towards biodiesel Production", International Journal of Renewable Energy Research-IJRER, Vol.6, No.4, August 2016.

[3] W.O. Amor et al., "Complementary Production of Biofuels by the Green Alga Chlorella vulgaris", International Journal of Renewable Energy Research-IJRER, Vol.5, No.3, March 2015.

[4] B.Verma and C.Balomajumder, "Algal Biodiesel Production: Comparison, Characterization and Optimization of Various Extraction Processes", International Journal of Renewable Energy Research-IJRER, Vol.6, No.3, July 2016.

[5] Abraham M. Asmare et al., "Theoretical Estimation the Potential of Algal Biomass for Biofuel Production and Carbon Sequestration in Ethiopia", International Journal of Renewable Energy Research-IJRER, Vol. 3, No. 3.

[6] Hamed SR, "Complementary production of biofuels by the green alga Chlorella vulgaris", International Journal of Renewable Energy Research-IJRER, vol.5, pp.936-43, 2015.

[7] Verma B, Balomajumder C., "Algal biodiesel production: Comparison, Characterization and optimization of various extraction processes", International Journal of Renewable Energy Research-IJRER, vol.6, pp.1071-5, 2016.

[8] Singh, A., et al., "Key issues to consider in microalgae based biodiesel production", Energy Educ. Sci. Technol. Part A Energy Sci., vol. 1, pp. 563-576, 2012.

[9] Reijnders, L., "Do biofuels from microalgae beat biofuels from terrestrial plants?", Trends in biotechnology, vol. 7, pp. 349-350, 2008.

[10] Zhao, B. and Y. Su, "Process effect of microalgal-carbon dioxide fixation and biomass production: a review", Renewable and Sustainable Energy Reviews, vol. 31, pp. 121-132, 2014.

[11] Mata, T.M., A.A, "Martins, and N.S. Caetano, Microalgae for biodiesel production and other applications: a review", Renewable and sustainable energy reviews, vol. 1, pp. 217-232, 2010.

[12] Richmond, A. and H. Qiang, "Principles for efficient utilization of light for mass production of photoautotrophic microorganisms", Applied Biochemistry and Biotechnology, vol. 1, pp. 649-658, 1997.

[13] Sharma, A.K., et al., "Impact of various media and organic carbon sources on biofuel production potential from Chlorella", 3 Biotech, vol. 2, pp. 1-12, 2016.

[14] Padmanabhan, P., "Technical insight on the requirements for CO2-saturated growth of microalgae in photobioreactors", 3 Biotech, vol. 2, pp. 119, 2017.

[15] Hreiz, R., et al., "Experimental and numerical investigation of hydrodynamics in raceway reactors used for algaculture", Chemical Engineering Journal, vol. 250, pp. 230-239, 2014.

[16] Labatut, R.A., et al., "Hydrodynamics of a large-scale mixed-cell raceway (MCR): experimental studies", Aquacultural engineering, vol. 2, pp. 132-143, 2007.

[17] Wang, Y.-H., et al., "Raceway design and simulation system (RDSS): An event-based program to simulate the day-to-day operations of multiple-tank raceways", Aquacultural Engineering, vol. 2, pp. 59-71, 2008.

[18] Prussi, M., et al., Experimental and numerical investigations of mixing in raceway ponds for algae cultivation. Biomass and bioenergy, 2014. 67: p. 390-400.

[19] Mendoza, J., et al., "Oxygen transfer and evolution in microalgal culture in open raceways", Bioresource technology, vol. 137, pp. 188-195, 2013.

[20] Brennan, L. and P. Owende, "Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products", Renewable and sustainable energy reviews, vol. 2, pp. 557-577, 2010.

[21] Ketheesan, B. and N. Nirmalakhandan, "Feasibility of microalgal cultivation in a pilot-scale airlift-driven raceway reactor", Bioresource Technology, vol. 108, pp. 196-202, 2012.

[22] Shang, H. and J. Scott, "Minimizing leakage from a smelter off-gas system by enhanced control", Journal of Cleaner Production, vol. 1, pp. 70-77, 2011.

[23] Gallardo-Rodríguez, J., et al., "New insights into shear-sensitivity in dinoflagellate microalgae", Bioresource technology, vol. 200, pp. 699-705, 2016.

[24] Jaouen, P., L. Vandanjon, and F. Quéméneur, "The shear stress of microalgal cell suspensions (Tetraselmis suecica) in tangential flow filtration systems: the role of pumps", Bioresource technology, vol. 2, pp. 149-154, 1999.

[25] Afshin Ghorbani et al., "The Biodiesel of Microalgae as a Solution for Diesel Demand in Iran", Energies, vol. 11, pp. 950, 2018.

[26] Montazeri-Najafabady, N., et al., "Effects of osmotic shock on production of β-carotene and glycerol in a naturally isolated strain of Dunaliella salina", Journal of Applied Pharmaceutical Science Vol, vol. 8, pp. 160-163, 2016.

[27] Morowvat, M.H. and Y. Ghasemi, "Culture medium optimization for enhanced β-carotene and biomass production by Dunaliella salina in mixotrophic culture", Biocatalysis and Agricultural Biotechnology, vol. 7, pp. 217-223, 2016.

[28] Mousavi, P., et al., "Investigating the effects of phytohormones on growth and β-carotene production in a naturally isolates stain of Dunaliella salina". 2016.

[29] Zarei, M., et al., "Effects of menthone and piperitone on growth, chlorophyll a and β-carotene production in Dunaliella salina", J Appl Pharm Sci, vol. 9, pp. 215-219, 2016.

[30] Murphy, C.F. and D.T. Allen, "Energy-water nexus for mass cultivation of algae. Environmental science & technology", vol. 13, pp. 5861-5868, 2013.

[31] Ho, S.-H., W.-M. Chen, and J.-S. Chang, "Scenedesmus obliquus CNW-N as a potential candidate for CO 2 mitigation and biodiesel production", Bioresource Technology, vol. 22, pp. 8725-8730, 2010.

[32] Tang, D., et al., "CO2 biofixation and fatty acid composition of Scenedesmus obliquus and Chlorella pyrenoidosa in response to different CO2 levels", Bioresource Technology, vol. 3, pp. 3071-3076, 2011.

[33] Matsumoto, Y., et al., Model analysis on carbonation reaction with redissolution of CaCO3. Proceedings of JCI, 1998. 20(2): p. 961-966.

[34] Putt, R., et al., "An efficient system for carbonation of high-rate algae pond water to enhance CO2 mass transfer", Bioresource technology, vol. 3, pp. 3240-3245, 2011.

[35] John, D.M., B.A. Whitton, and A.J. Brook, "The freshwater algal flora of the British Isles: an identification guide to freshwater and terrestrial algae", Cambridge University Press, Vol. 1. 2002.

[36] Eaton, A.D., L.S. Clesceri, and A.E. Greenberg, "Standard methods for the examination of water and wastewater", American Public Health Association, Washington, DC, 1995.

[37] Ho, S.-H., et al., "Engineering strategies for improving the CO 2 fixation and carbohydrate productivity of Scenedesmus obliquus CNW-N used for bioethanol fermentation", Bioresource technology, vol. 143, pp. 163-171, 2013.

[38] Ono, E. and J.L. Cuello, "Carbon dioxide mitigation using thermophilic cyanobacteria", Biosystems engineering, vol. 1, pp. 129-134, 2007.

[39] Mooney, B.D., et al., Lipid, "Fatty acid, and sterol composition of eight species of kareniaceae (dinophyta): chemotaxonomy and putative lipid phycotoxins1", Journal of Phycology, vol. 1, pp. 101-111, 2007.

[40] Rasoul-Amini, S., et al., "PCR amplification of 18S rRNA, single cell protein production and fatty acid evaluation of some naturally isolated microalgae", Food Chemistry, vol. 1, pp. 129-136, 2009.

[41] Sobczuk, T.M., et al., "Carbon dioxide uptake efficiency by outdoor microalgal cultures in tubular airlift photobioreactors", Biotechnology and bioengineering, vol. 4, pp. 465-475, 2000.

[42] De Morais, M.G. and J.A.V. Costa, "Carbon dioxide fixation by Chlorella kessleri, C. vulgaris, Scenedesmus obliquus and Spirulina sp. cultivated in flasks and vertical tubular photobioreactors", Biotechnology letters, vol. 9, pp. 1349-1352, 2007.

[43] Hosseini, N.S., et al., "Microalgae cultivation in a novel top-lit gas-lift open bioreactor", Bioresource technology, vol. 192, pp. 432-440, 2015.

[44] Mayer, A., et al., "Problems of design and ecological considerations in mass culture of algae", Biotechnology and Bioengineering, vol. 2, pp. 173-190, 1964.

[45] Al-Shayji, Y., et al., "Production and separation of algae in a high-rate ponds system", Environment international, vol. 4, pp. 541-550, 1994.

[46] Chinnasamy, S., et al., "Biomass and bioenergy production potential of microalgae consortium in open and closed bioreactors using untreated carpet industry effluent as growth medium", Bioresource Technology, vol. 17, pp. 6751-6760, 2010.

[47] Bao, Y., et al., "In situ carbon supplementation in large-scale cultivations of Spirulina platensis in open raceway pond", Biotechnology and bioprocess engineering, vol. 1, pp. 93-99, 2012.

[48] Chiaramonti, D., et al., "Review of energy balance in raceway ponds for microalgae cultivation: re-thinking a traditional system is possible", Applied Energy, vol. 102, pp. 101-111, 2013.

[49] Ryu, H.J., K.K. Oh, and Y.S. Kim, "Optimization of the influential factors for the improvement of CO2 utilization efficiency and CO2 mass transfer rate", Journal of Industrial and engineering chemistry, vol. 4, pp. 471-475, 2009.

[50] Hsueh, H., et al., "Carbon bio-fixation by photosynthesis of Thermosynechococcus sp. CL-1 and Nannochloropsis

oculta", Journal of Photochemistry and Photobiology B: Biology, vol. 1, pp. 33-39, 2009.

[51] Chiu, S.Y., et al., "The air-lift photobioreactors with flow patterning for high-density cultures of microalgae and carbon dioxide removal", Engineering in life sciences, vol. 3, pp. 254-260, 2009.

[52] Lv, J.-M., et al., "Enhanced lipid production of Chlorella vulgaris by adjustment of cultivation conditions", Bioresource Technology, vol. 17, pp. 6797-6804, 2010.

[53] Westerhoff, P., et al., "Growth parameters of microalgae tolerant to high levels of carbon dioxide in batch and continuous-flow photobioreactors", Environmental technology, vol. 5, pp. 523-532, 2010.

[54] Fontenot, R.L., "An evaluation of reference evapotranspiration models in Louisiana", Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Natural Sciences In The Interdepartmental Program of Natural Sciences by Royce Landon Fontenot BS, Louisiana State University, 2004.

[55] Pate, R., G. Klise, and B. Wu, "Resource demand implications for US algae biofuels production scale-up", Applied Energy, vol. 10, pp. 3377-3388, 2011.