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Design, Fabrication, and Performance Evaluation of Open Raceway Ponds for the Cultivation of *Chlorella vulgaris* Beijerinck in the Philippines

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Two pilot-scale open raceway pond systems were designed and fabricated in the University of the Philippines Los Baños (UPLB) for the cultivation of *Chlorella vulgaris* Beijerinck to observe the biomass productivity of the alga in an open condition in the Philippines. One design was an oval track with a middle island, while the other was a multi-stage raceway pond (MSRP) consisted of several sections separated by baffles. The pond designs aimed to accommodate 1,000 L of culture. The nutrient media used was composed of urea, NPK (16-20-0), $FeCl_3$, and Na_2EDTA – a locally formulated medium that sustains the growth of the species. Paddlewheel was installed to provide mixing, which was turned on during the daytime, while aeration was continuously supplied through perforated air-distributor PVC pipes installed on the pond floor. Only natural light was utilized, and no lighting was provided during the night. The growth rate was generated by monitoring the biomass concentration in the pond through spectrophotometry at 425 nm, where optical density and biomass concentration relationship was initially established. Using the equation for first-order kinetics and taking the points from the exponential phase, the specific growth rate of *Chlorella* obtained from the oval raceway pond was computed to be 0.007308 h^{-1} with doubling time of 94.84 h. The biomass productivity rate was computed to be 308.49 g/m^3-d or equivalent to 63.24 g/m^2-d. On the other hand, the MSRP obtained a specific growth rate of 0.003389 h^{-1} with a doubling time of 204.55 h and equivalent biomass productivity of 302.19 g/m^3-d or 60.44 g/m^2-d. The biomass productivity obtained is comparable, even superior to other commercial open pond cultivation using *C. vulgaris*.

Keywords: biomass productivity, costing, doubling time, multi-stage, open raceway pond design, specific growth rate

INTRODUCTION

Sustainable development is a global key issue today. The world population is constantly increasing with an average rate of 1.20%/yr since 2000 that makes food and energy sources, among many, become subjects of concern. Fossil fuels continue to dominate the energy market with more than 80% share on the total global energy demand as of 2017, but this landscape is being challenged by the depleting resources and environmental pressures brought about by the increase in energy demand, projected at about 27% from 2017–2040 (Eule 2018).

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In the Philippines, the production of fossil oil, natural gas, and coal is very minimal; hence, the development and optimal use of renewable resources is supported by the Department of Energy for the country's low emissions strategy, energy security, and access to energy. The country has the Renewable Act of 2008 and the Biofuels Act of 2006, which supports the use of biomass for energy production. In this study, the cultivation of the selected microalgae species, *Chlorella vulgaris*, in open systems is observed to analyze its feasibility for biofuels production.

Microalgae are considered as a promising biodiesel feedstock since it grows easily. Unlike the first and second-generation biodiesel sources (crops), which are harvested annually or biannually, microalgae can have harvesting cycles as short as 10 d (Dragone *et al.* 2010). Microalgae have the ability to convert over 10% of captured solar energy into biomass in contrast to 0.5% average photosynthetic efficiency of conventional terrestrial crops (Costa and de Morais 2010). Beyond remarkable growth rates, high oil content of microalgae compared to first and second-generation biofuel feedstock is also a major benefit, which when microalgae with 30% oil content can have oil yield per hectare about 11 times more than palm oil and about 92 times more than soybean (Mata *et al.* 2010).

Aside from its superior oil yield and conservative growth needs, microalgae can be environmentally beneficial. It was reported that a kilogram of microalgal biomass (dry basis) utilizes 1.83 kg of carbon dioxide (CO_2); thus, biofixation of waste CO_2 by microalgae can lead to significant environmental reinforcement (Brennan and Owende 2009). For CO_2-producing industries, greenhouse gas emission reduction can be achieved while producing biodiesel (Mata *et al.* 2010). The Philippines ranked fifth in the most vulnerable countries to climate change in the Global Risk Index 2018 (Lopez 2018), which necessitates active participation in curbing CO_2 emissions. Additionally, protein-rich microalgal biomass can also cater to the Philippines' increasing demand for feeds for livestock and poultry, since the domestic feed-consuming industries almost completely rely on the importation of soybean meal (Arcalas 2018).

The Philippines is home to diverse species of microalgae. *C. vulgaris* is a green alga with a huge potential as biodiesel feedstock. *C. vulgaris* has lipid content ranging from 14–22% (w/w) on a dry basis (Rengel 2008). The whole biomass can also be converted to biocrude oil via thermochemical processes; hence, biomass productivity is significant. Growth requirement for microalgal species consists primarily of CO_2 and water but can be further improved with adequate aeration, enough lighting, and appropriate nutrient loading. Microalgal cultivation can be done via closed or open systems. Photobioreactors (PBRs) are closed systems that provide a controlled environment for algal growth. In these systems, high productivity can be attained but are costly in terms of capital costs. On the other hand, open systems include a shallow enclosure, with raceway ponds requiring large open water raceway tracks wherein algae and nutrients are pumped around by a motorized paddle. This is simple to construct, easy to operate, and entails low capital and operating costs (Liang *et al.* 2015; Narala *et al.* 2016). Techno-economic studies have shown the significance of open pond cultivation to enable economically viable algal biomass production, as demanded for subsequent conversion to commodity fuels (Davis *et al.* 2016).

Several commercial-scale cultivations of microalgae using open ponds have been demonstrated by several companies in different countries such as the Sapphire Energy in New Mexico, Muradel in Australia, Solazyme now TerraVia in US and Brazil, and Cellana in Hawaii (ETIP 2020). These models utilized the use of an oval raceway pond.

This study aimed to design, fabricate, and evaluate the performance of two pilot-scale open raceway ponds for the cultivation of local *C. vulgaris* species in terms of specific growth rate, doubling time, and biomass productivity. From the most commercially used oval raceway pond, which has good axial mixing, a new design by the installation of baffles – creating multi-stage along the path of the culture – was built and evaluated with the aim of improving radial mixing. The result of the research will aid in the sustainability of biofuel production in the Philippines by verifying the potential of this alternative feedstock source – cultivated in open raceway ponds. The results will also be used to estimate feasibility in terms of cost in comparison with existing data.

MATERIALS AND METHODS

Design and Fabrication of the Raceway Pond

Dimensions. The design of the oval raceway pond (Figure 1) was scaled-up from a laboratory-scale raceway pond designed by Sanchez *et al.* (2007) using the pond length to width ratio of 3.5:1. The dimensions of the pond were computed based on the ideal height of 0.2 m (Huang *et al.* 2010) and the desired working volume of 1 m^3. A practical-sized island was installed at around 12% of the pond width (Ben-Amotz n/d). The final dimensions of the pond were L = 4.55 m and W = 1.30 m (rectangular field), D = 1.30 m (half-circle ends), and H = 50 cm – giving a total pond volume of 3,321.88 L.

On the other hand, the design specifications of the MSRP was based on the horizontal flat-plate PBR

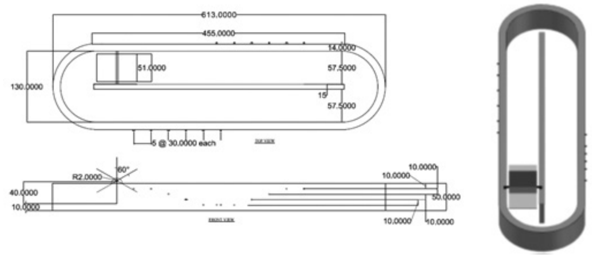

Figure 1. Top and side view of the oval open raceway pond.

model of Reyna-Velarde *et al.* (2009) with the following measurements: L = 0.67 m and W = 0.57 m. Following the width to length ratio of 0.85, the dimensions of the MRSP to contain 1,000 L of culture were L = 2.42 m, W = 2.06 m, and H = 0.20 m. The final depth of the design was adjusted to 0.50 m (Figure 2) to avoid spilling of culture and provide an allowance for increasing volume productivity per area.

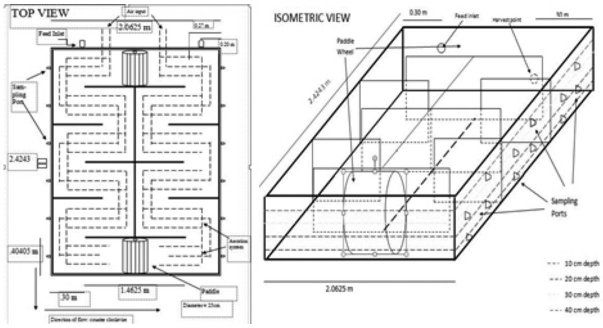

Figure 2. Top and isometric view of the multi-stage open raceway pond.

A baffle system was employed to improve culture mixing in the reactor. Since the microbial culture has the tendency to settle at the bottom, mixing efficiency of the reactor was considered as a major factor for culture growth. The ideal reactor must provide a good axial and radial mixing. Two large baffles and eight small baffles were installed in the reactor. The small baffles have a dimension of 0.7313 m x 0.5 m while the large baffles have a dimension of 1.4625 m x 0.5 m.

The materials of construction used in the ponds were concrete, cement, and hollow blocks. A cement coating was applied to the walls and floor of the reactor to make sure that there were no leaks and to minimize water absorption. The baffles were made from aluminum flat sheets with steel primer to prevent rusting. A steel bar was used as the frame of the aluminum flat sheet.

Paddlewheel system. A stainless-steel paddlewheel was designed to provide mixing in the pond. According to Ben-Amotz (n/d), a single paddlewheel can be used for areas up to 3,400 m^2. The fabricated oval pond has an area equivalent to 6.6438 m^2, while the MSRP has a size of 5 m^2. The paddlewheel has a radius of 25 cm with a speed of 114 rpm, and a pulley system to reduce the speed to 21 rpm. This falls within the range of the ideal paddlewheel speed of 5–30 rpm (Ben-Amotz n/d). The paddlewheel was turned on during the daytime.

Figure 3. Paddlewheel and pulley system of the open raceway ponds.

Aeration. Air-distributor pipes were installed in the pond using 1-in PVC pipes bore with holes to the size of a diameter of a standard 1-in nail. This perforated pipe design (Figure 4) improves the mixing of the culture at the bottom. The holes have a 5-cm interval.

Figure 4. Perforated pipe design.

Three sets of these pipes ran along the raceway floor (Figure 5). They were connected to the Vespa SF 201P compressor or a GF-180 air blower. Air distribution was controlled by a set of valves connected to the pipes. Aeration was continuously supplied throughout the study.

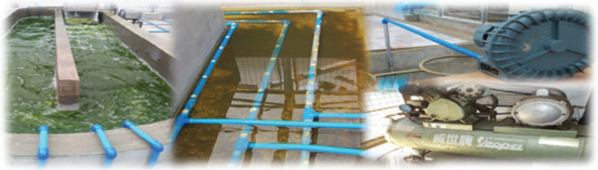

Figure 5. Air compressor and pipes in the pond for aeration.

Sampling ports. Sampling ports were located on both sides of the pond at different heights for the determination of biomass concentration. A total of 12 ports were fixed. Each side of the oval raceway pond has four ports per sampling height located at 40, 30, 20, and 10 cm, and additional ports for feeding at 40 cm and harvesting at 10 cm height (Figure 6). The ports were laterally separated by 30 cm. The growth curves were generated from four sampling ports located at 20 and 10 cm for both sides of the pond.

Figure 6. Sampling ports of the oval raceway pond at different heights.

For the MSRP, the sampling ports were located at 5, 15, 25, and 35 cm (Figure 7). The experiment used eight sampling ports, four of which were placed at a height of 5 cm and the other four were located at a height of 15 cm – two of each are located on the opposite sides of the pond adjacent to the side of the paddlewheel.

Figure 7. Sampling ports of the multi-stage open raceway pond at different heights.

Gate valves of 1-in diameter were used as ports. A drain was also bored at the pond floor, controlled by a valve, to easily withdraw pond contents.

Greenhouse cover. A greenhouse was built to provide cover for the open raceway ponds. The walls were made of steel screens and concrete. The greenhouse wall allows the air to pass through from all directions. The roof, on the other hand, is made of a plastic material, which permits enough light to penetrate for the photosynthetic processes of *C. vulgaris*, and to limit ultraviolet rays. Additionally, the roof was constructed with a sliding mechanism at the center, which may be opened or closed depending on the weather condition. The cover was installed to address the difficulty in controlling weather conditions concerning open ponds.

Figure 8. The greenhouse cover of the open raceway pond.

Cultivation of *C. vulgaris* in the Open Raceway Ponds

The *C. vulgaris* species used in this study is locally isolated from Laguna de Bay and was chosen for its good growth, ease in culturing, and less susceptibility to contamination out of the 30 strains screened in the Phycology Laboratory, Institute of Biological Sciences, UPLB.

The cultivation of *C. vulgaris* started with laboratory-scale productions on PBR systems such as polyethylene terephthalate bottles (mini PBRs), plastic bags, and previously designed PBRs currently available (Figure 9). Initially, the culture media were prepared in the Phycology laboratory at the Institute of Biological Sciences, UPLB. The nutrient media contained 0.17192 g urea, 0.02073 g NPK (16-20-0), 0.01 $FeCl_3$, and 0.01 g Na_2EDTA per liter of tap water (Martinez-Goss *et al.* 2010).

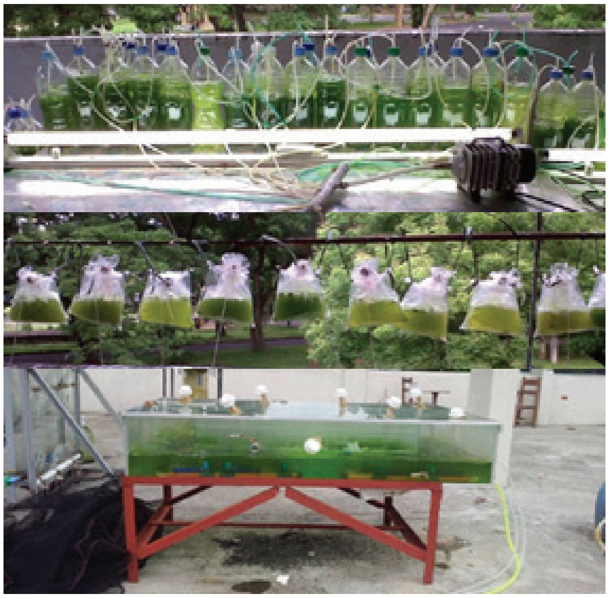

Figure 9. Laboratory-scale productions of inoculum.

In the laboratory cultivation, the aseptic technique was applied to ensure monoculture cultivation. The prepared media were sterilized in an autoclave at 15 psi and 121 °C for 15 min. The open raceway pond is highly susceptible to contamination; thus, it must be minimized.

As a rule of thumb for bioreactors, at least 10% of the working volume must be mature culture inoculum.

The fabricated oval pond held a volume equivalent to 1,361.78 L at 20.5-cm depth; hence, at least 136.178 L mature inoculum was required to begin the raceway pond cultivation, while 100 L was required to start the MSRP at 20 cm.

The maturity of the inoculum was indicated by a deep apple green color or displays an optical density of 0.10 at 425 nm.

The reactors were disinfected prior to inoculation. The pond was filled with tap water and chlorine and was allowed to stand for 24 h. The pond was drained and washed with tap water until no smell of chlorine was detected. Cultivation immediately followed (Figure 10).

Figure 10. Inoculated *C. vulgaris* culture in the open raceway ponds

The oval raceway pond was operated from 14 May 14 – 14 Jun 2012 with temperature ranging from 24–34 °C averaging to 29.7 °C, while the MSRW operated from 28 May – 16 Jul 2012 with temperature ranging 19.7–31.5 °C averaging to 28.34 °C. Only natural light was utilized, and no lighting was provided during the night.

Sampling and Data Gathering

In order to monitor the growth of microalgae in the raceway pond, a correlation between biomass concentration and optical density was first established. One hundred milliliters (100 ml), 50 ml, and 25 ml were collected from the pond and diluted to 100 ml. Afterward, the optical densities of each sample were determined using Hach DR 2800 Visible Spectrophotometer at 425 nm, where excitation light wavelength was observed for the *Chlorella* sp. used. Green algae have predominant pigment Chl b, which absorbs in the violet (400–425nm) and the red (640–740nm) regions (Nobel 1991).

The corresponding biomass concentration for each OD was measured by drying the same amount of culture in the oven at 80 °C for 8 h. The weight of the biomass for each sample was determined by subtracting the initial weight of the petri dish used. A linear equation describing the relationship of the optical density and biomass concentration was derived by plotting the best fit line. However, the derived linear equation would give equivalent biomass at zero optical density, which defies logic. To address this discrepancy, the equation of the line was modified to intercept at (0,0). Two trials were done, and the average was taken and used for the purposes of the study.

Culture sampling was done three times a day at 6-h intervals. Five milliliters (5 ml) of culture was withdrawn from the sample ports and subjected to spectrophotometry using the same Hach DR 2800 Visible spectrophotometer. For each sampling, factors such as temperature, pH, and pond height were noted.

Performance Assessment of the Microalgal Cultivation

Specific growth rate. The growth profile of *C. vulgaris* is illustrated by plotting biomass concentration versus the time elapsed from the start of cultivation. The specific growth rate was calculated using Equation 1, the doubling time was determined using the first-order kinetics shown in Equation 2, and the biomass productivity was computed based on Equation 3.

$$\mu_{\mathrm{nm}} = \frac{\ln(C_{\mathrm{biomass,2}}) - \ln(C_{\mathrm{biomass,1}})}{t_2 - t_1} \quad (1)$$

$$t_{doubling} = \frac{\ln(2)}{\mu_{nm}} \quad (2)$$

$$r_{\mathrm{biomass\ productivity}} = \text{biomass concentration x } \mu_{\mathrm{nm}} \quad (3)$$

RESULTS AND DISCUSSION

Determination of the Relationship of Biomass Concentration to Optical Density

The data for the biomass concentration versus optical density (Table 1) were plotted and linear regression was employed to get the working equations (Equations 4 and 5) for the determination of biomass concentration during the sampling period.

Table 1. Biomass concentration and optical density @425 nm relationship.

	Trial 1			Trial 2		
OVAL						
OD, 425 nm	0.308	0.813	1.606	0.319	0.817	1.64
Biomass content (g/L)	0.03	0.841	1.773	0.234	0.589	1.501
MRSP						
OD, 425 nm	0.242	0.769	1.483	0.242	0.769	1.483
Biomass content (g/L)	0.23	1.43	2.03	0.43	0.58	2.19

$$C_{\text{biomass, oval}} = 0.9670\ OD_{425nm} \tag{4}$$

$$C_{\text{biomass, MSRP}} = 1.3975\ OD_{425nm} \tag{5}$$

Growth Rate of *C. vulgaris* in the Open Raceway Ponds

With the determination of the biomass concentration and constant monitoring of the pond volume for 685.50 h for the oval raceway pond and 1,164 h for the MSRP, the growth curves at 425 nm from the sampling ports were plotted to observe divergence in the concentration at different locations (Figures 11 and 12).

For the oval raceway pond in Figure 11, Port 1 (20 cm depth from floor, located on the paddlewheel side of the pond) showed modest growth data, which may be due to its direct proximity to the paddlewheel that ensures proper mixing; Port 2 (10 cm depth on the side of the paddlewheel) exhibited higher growth curve than Port 1, which can be attributed to some biomass settling even though there were aerators installed on the floor of the pond; Port 3 (20 cm depth opposite the paddlewheel) obtained growth curve close to Port 1, which could prove effective axial mixing along the oval raceway pond (axial mixing is the flow parallel to the direction of the impeller/fluid); and Port 4 (10 cm depth opposite the paddlewheel) showed the greatest fluctuation, which may be an indicator that this has the poorest radial mixing due to inadequate aeration since the microalgae tend to have settled, hence obtaining higher biomass concentration. Although the

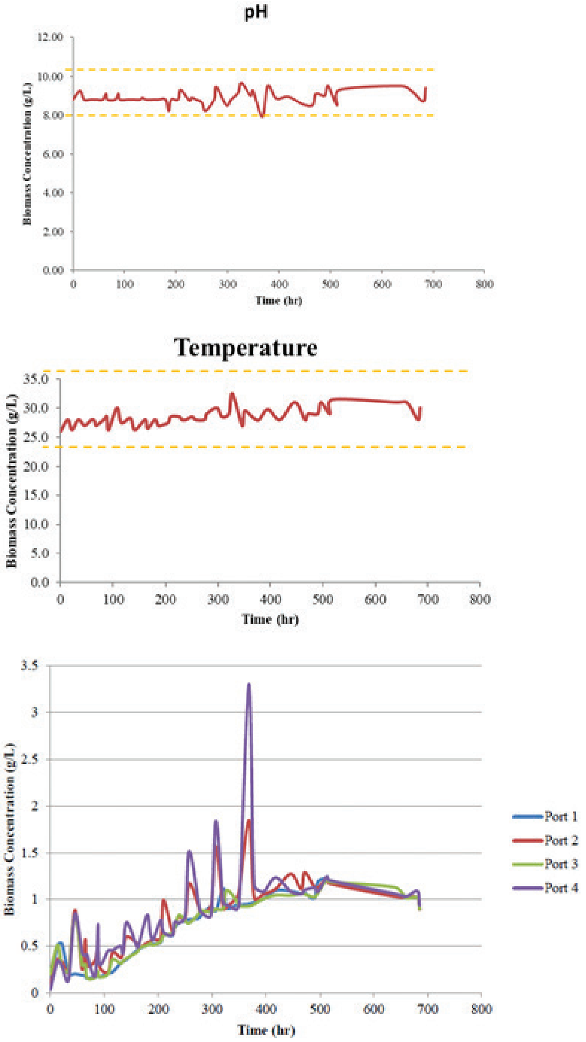

Figure 11. Parameters profile and growth curve of *C. vulgaris* in the oval raceway pond from four sampling ports measured at 425 nm; Ports 1 and 3 are located at 20 cm, Ports 2 and 4 at 10 cm.

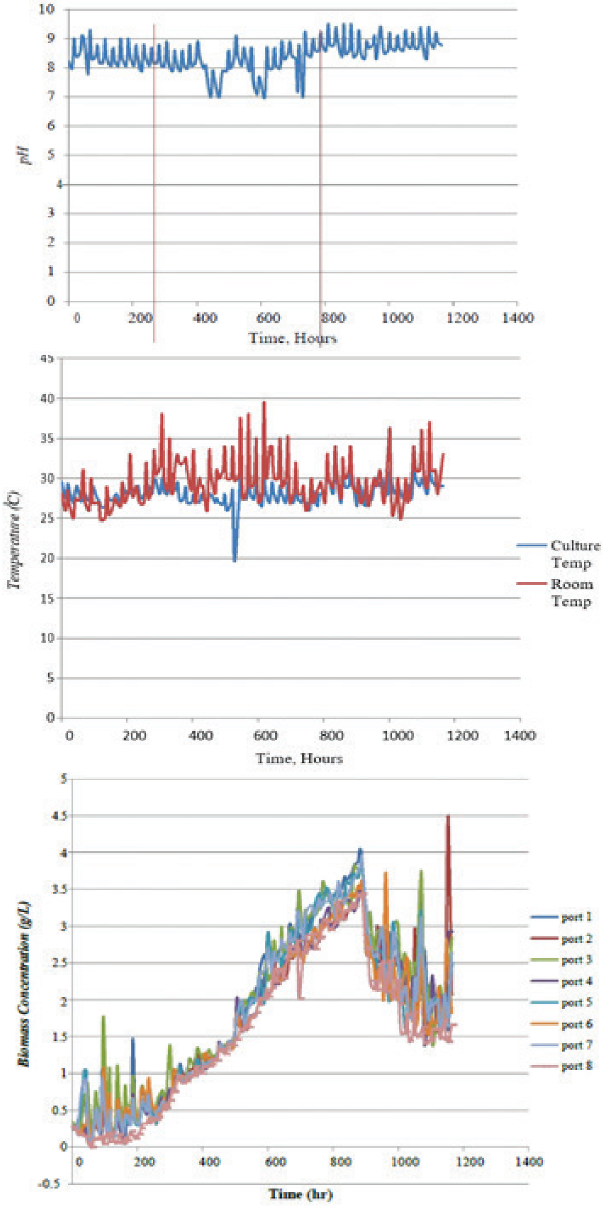

Figure 12. Parameters profile and growth curve of *C. vulgaris* in the MSRP from eight sampling ports measured at 425 nm; Ports 1, 3, 5, and 7 are located at 5 cm, the rest at 15 cm.

readings showed that concentration profile along the locations followed the same trend, design improvements for addressing biomass settling can be done given the sudden fluctuations or non-homogeneity in biomass concentration at a given period.

For the MSRP, the installation of the baffle system was initially conceptualized to provide a better mixing profile for the pond. Ports 1, 3, 5, and 7 are located at 5-cm culture height, and the remaining ports are located at the 15 cm liquid height. In the experiment, Port 8 had the lowest amount of biomass concentration measured, which could be due to its position at a higher liquid level and its proximity to the suction area of the impeller where velocity is high; hence, biomass is less concentrated. Ports 3, 5, and 7 had the highest biomass concentration, which can be attributed to biomass settling – among which, Port 5 had the highest biomass concentration. This may be because the flow of liquid is lowest at this stage of the reactor as it is farthest from the impeller but, although there was a slow movement, vortex and eddies were visible. Still evident with MSRP, microalgal biomass tends to settle at the bottom of the reactor. The lower the source of the samples the higher is the concentration.

Meanwhile, among the samples obtained from the higher sampling ports, both the sampling ports labeled 4 and 6 exhibited higher biomass concentration. In these stages, the mixing is just enough to have a proper mixing in both radial and axial flow. The flow in this area is not too turbulent.

The different mixing patterns due to the employment of the baffle system is the major advantage of the MRSP compared to the conventional raceway pond. Observing the graphs, the MRSP gave a more precise measurement than along an oval raceway pond. However, an MRSP may require a higher impeller speed, which equates to higher power consumption as compared to the oval raceway pond with smooth curves that minimize energy loss.

The period of the experiment for the oval raceway pond started on 14 May 2012, two weeks before the MSRP was operated. The onset of the cultivation MSRP was faced with the change in weather in the Philippines and was heavily affected by Typhoon Mawar (local Ambo) on the 4th day of cultivation. The roof installed was not able to carry the rainfall and the culture was contaminated by rainwater. Clumps of biomass, foaming, and a slight change of color were observed days after the addition of rainwater.

The typhoon persisted until 13 Jun 2012, which slowed down the lag phase of the culture in the MSRP for about 10 d (Figure 14), unlike in the oval raceway that took only about four days before entering the exponential phase (Figure 13). The experiment was carried on, waiting until growth entered the death phase. The experiment was ultimately halted when the culture eventually did not recover after another heavy rainfall from the storm that fully contaminated the culture on 04 Jul 2012 (at 900 h of MSRP).

The growth regimes of the species are classified in Figures 13 and 14. Region I is the period of acclimatization often referred to as the lag phase. Very little growth was observed at this phase. During this period, it is possible that cells would only increase in size but not reproduce. Region II is the region of accelerated growth. This is the phase prior to the period where the maximum growth rate is observed. Region III is the exponential growth phase wherein cells reproduce rapidly. This stage also reaches the highest biomass concentration during the entire growth of the cells. Region IV is the phase where growth acceleration begins to fall. The nutrient is continuously depleted as cells reproduce and continue to feed along with their offspring while nutrients were not supplied after the initial inoculation for this batch cultivation. Region V is the phase where growth no longer occurs. Lastly, Region VI shows the period where microalgae start to die.

Open ponds are acknowledged to be prone to pond crashes and biomass loss. The country experiences rainfall half of the year, which could lead to such outcomes. The cultivation set-up suffered from the effects of a storm; the

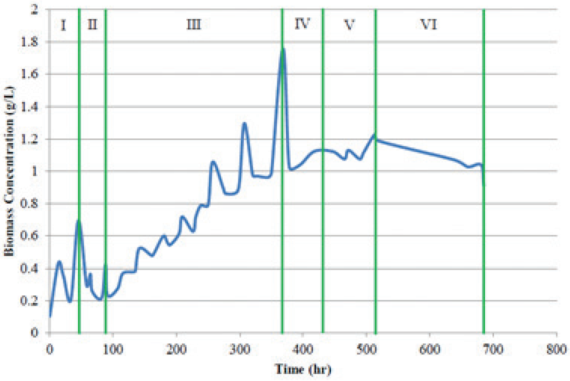

Figure 13. Averaged growth curve of *C. vulgaris* in the oval raceway pond measured at 425 nm.

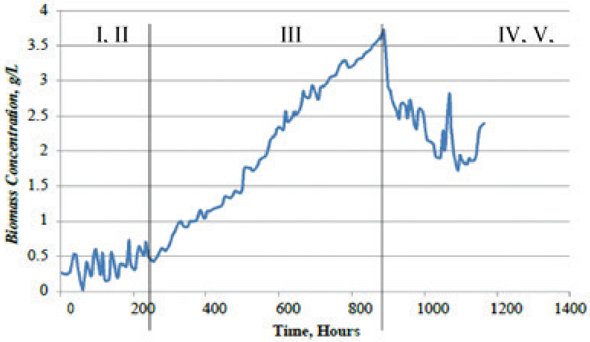

Figure 14. Averaged growth curve of *C. vulgaris* in the MSRP measured at 425 nm.

sliding roof installed was detached, leaving the culture contaminated with plenty amount of rainwater that immediately resulted in culture death (Figure 14). Hence, a better greenhouse design should be given importance to future studies.

Determination of the Specific Growth Rate

The specific growth rate is an important factor in determining pond parameters, such as doubling time and flow rate to be used for continuous cultivation. It is a measure of the potential of a microalgal cell to reproduce. Thus, it is important for production systems to maximize this value. Taking the region of exponential growth for the oval raceway pond (Figure 13), the growth rate was calculated using the points 82.5 h (0.2175 g/L) to 368.5 hours (1.7588 g/L). Meanwhile, the exponential phase was observed from 252 h (0.4306 g/L) to 888 h (3.7157 g/L) for the MSRP (Figure 14).

The specific growth rates were computed to be 0.007308 h^{-1} with a doubling time of 94.84 h for the oval raceway pond, and 0.003389 h^{-1} with doubling time of 204.55 h, for the oval and MSRP, respectively. The biomass productivity rates were computed to be 308.49 g/m^3-d or equivalent to 63.24 g/m^2-d for the oval RP, while 302.1926 g/m^3-d or equivalent to 60.44 g/m^2-d biomass productivity were obtained for the MSRP (Table 2). From a previous study conducted in the department for the same species and culture medium using a locally designed and fabricated PBR, the specific growth rate attained was 0.0106 h^{-1} (Santiago *et al.* 2013), which is about 1.45 faster than the result of this study. This may be attributed to the controlled environment and continuous lighting employed during the study.

Table 2. Summary of specific growth rate, doubling time, and biomass productivity derived using first-order kinetics for the designed and fabricated open raceway ponds.

Parameters	Averaged parameters	
	Oval	Multi-stage
Δln	2.0902	2.1552
Δt (hr)	286	636
μ (hr^{-1})	0.0073	0.0034
$t_{doubling}$ (hr)	94.8442	204.5496
$r_{biomass\ productivity}$ (g/m^3-d)	308.4986	302.1926
$r_{biomass\ productivity}$ (g/m^2-d)	63.2422	60.4385

Comparing the results of this study with previous studies gathered by Davis *et al.* (2016) (Figure 15), the performances of the fabricated ponds are competitively comparable.

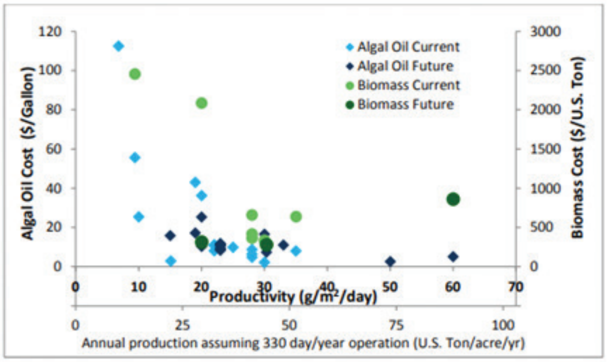

Figure 15. Overview of published estimates for cultivation and processing costs of biomass and algal oil (Davis *et al.* 2016).

From Figure 15, it will be observed that algal biomass price ranges from $270–2,450/T, translating to $2–110/gal algal biofuels, within the algal production range of 7–60 g/m^2/d annual average at 330-d/yr operation. Estimates were based on the 2011 US dollar exchange rates. Translating to 2019 dollars and converting to Php/L biofuels, the amount ranges from Php 31.32–1,722.61/Lalgal biofuel. This report from the National Renewable Energy Laboratory suggests that biomass productivity of algal systems must be targeted to at least reach 25-g/m^2/d annual average to avoid dramatic penalties on the minimum biomass selling price.

Using the values obtained in the study of about 308 g/m^3-d and 4-d doubling time, algal biomass in this set up would cost USD 2,061.69/T (Table 3). This is inside the range as abovementioned but much bigger from the expected price of about $270/T, considering the biomass productivity is already in the upper range of 7–60 g/m^2-d.

Table 3. Costing for the open raceway pond cultivation of *C. vulgaris* using locally formulated fertilizer medium with biomass productivity of 308 g/m^3-d.

Cost	Unit	Price	Total amount
Electricity	0.37 kWh/ m^3-d^a	\$0.20/kWh^b	\$0.30
Water	1 m^3	\$0.40/m^{3c}	\$0.40
Nutrients	For 1 m^3	\$1.62/m^{3d}	\$1.62
Harvesting	0.1 kWh/m^{3a}	\$0.20/kWh	\$0.02
Dewatering	1 kWh/m^{3a}	\$0.20/kWh	\$0.20
Total			\$2.54
Biomass yield	308 g/m^3-d		1.232 kg
Rate (2020 USD)			\$2,061.69/T

Sources: [a]Wu and Chang (2019); [b]Asian Power (2019); [c]Cahiles-Magkilat (2020); [d]author's actual cost

On the other hand, the use of a hydrothermal liquefaction technology, which can process algae at 5–20% concentration to obtain 67–76% w/w biocrude oil, improves feasibility (Wibawa *et al.* 2018). Using 67% w/w conversion, algal crude oil would amount to \$0.283/L [\$2,061.69/T biomass * (1 T biomass / 0.67 T crude oil) * (0.000092 T/L)]. The crude oil price before the COVID-19 pandemic trades at around \$60/barrel (Markets Insider 2020), equivalent to \$0.377/L (1 barrel = 158.98 L), which makes the local production competitive to the commercial crude oil price.

CONCLUSION

The study has proven that biomass productivity in open raceway ponds is outstanding. Although if compared to the PBR that cultivated the same species using the same nutrient medium (Santiago *et al.* 2013), where the performance of the open raceway pond falls inferiorly, the biomass productivity obtained reached the minimum commercial production target of 25 g/m^2-d (Davis *et al.* 2016). The experiment was conducted with minimal adjustments; hence, this initial performance can be further improved. Moreover, worldwide large-scale production facilities currently are 95% open pond (Kumar *et al.* 2015), which proves that this type of production has a lot of potential.

Comparing the two designs, it can be concluded that more precise measurements were obtained from MSRP, hence proving a better mixing profile for the pond. The baffles have improved both the axial and radial mixing, which is ideal for cultures that tend to settle at the bottom. However, proving that the oval raceway pond can achieve doubling time of about 4 d for *C. vulgaris*, which is at par with the BG-11-cultured *C. vulgaris* with enabling growth parameters of 4.2 d (El-Ibiari *et al.* 2015), oval raceway ponds may still be superior especially if the multi-stage raceway design will use more energy for the paddlewheels when compensating for the energy lost because of the baffles installed.

While contamination and culture crashes are a problem with open systems, recent studies have focused on employing a two-stage hybrid system connecting the cultivation from PBRs to open pond systems, aiming to separate growth rate and lipid production optimization if biodiesel production is targeted. High-density contamination-free inoculum can be grown in PBRs and used for subsequent cultivation in low-cost open ponds under nutrient-deprived conditions that will then drive lipid productivity, ultimately leading to improved economic viability (Wensel *et al.* 2014; Narala *et al.* 2016; Nagappan *et al.* 2019). This proves that the use of open systems in the feasibility of microalgal mass production is indispensable.

The result of this study can contribute to the database for more accurate costing estimates. And to recommend, studies on how to maintain acceptable productivity throughout the year is one focus of further investigations. When acceptable biomass productivity is attained and maintained, the microalgal system could be a sustainable bioenergy source in the Philippines.

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