Microalgae as Sustainable Energy and Its Cultivation

S. S. Sawant\textsuperscript{a}, B. D. Gajbhiye\textsuperscript{a}, C. S. Mathpati\textsuperscript{a,*}, Reena Pandit\textsuperscript{b}, A. M. Lali\textsuperscript{a,b}

\textsuperscript{a} Department of Chemical Engineering, Institute of Chemical Technology, Matunga, Mumbai 400019, India
\textsuperscript{b} DBT-ICT Centre for Energy Biosciences, Institute of Chemical Technology, Matunga, Mumbai 400019, India

*Corresponding author Email: cs.mathpati@ictmumbai.edu.in
Ph. No. +91-22-33612017 Fax: +91-22-33611020

Abstract:
Growth of every country is depended on the ability to supply energy as per demand. Weather we notice it or not, the fact is energy is important in our daily life. The predicted expansion of world's population is at least 9 billion by 2050, correlates increase of energy use globally to 812 quadrillion (10^{15}) kJ by 2035 from 533 quadrillion kJ in 2008. A key challenge is to meet the growing demand for energy in a safe and environmentally responsible manner. Sustainable energy serves the needs of the present without compromising the ability of future generations to meet their needs. Technologies that promote sustainable energy include renewable energy sources, and bioenergy is one of the types of renewable energy. Bioenergy is any organic material which can store sun light in the form of chemical energy. Algal biofuel has a potential to reduce the demand of fossil fuels for energy requirements. Algae production do not have a stringent requirement of environmental conditions and can be produced in aqueous suspensions where sufficient light and carbon dioxide is available. Biofuels from algae have a high lipid density (15-300 times higher than traditional crops) as compared with other terrestrial crops. Algae have a harvesting cycle of 1–10 days. The amount of biomass is doubled typically within 24 hours under optimal growth conditions (enough nutrients, sunlight etc.). The two major bioreactor classes of algae growth systems are open ponds and closed reactors. The most common growth systems used for commercial purposes are open pond. Open ponds are relatively inexpensive compared to closed photo bioreactor. Algae cells are sensitive to hydrodynamic stress. The concept of cell damage correlates interaction between free cells and isotropic turbulence eddies based on Kolmogorov's theory. When the micro-eddies size is close to the cell dimension, cell damage is higher; therefore, one should adjust the fluid flow in the open pond to maintain length of micro-eddies larger than the cell size. In the present investigation CFD code was used to study shear stress in open pond with side entry axial flow impeller. Three different channel lengths to width ratio were investigated with respect to size of micro eddies and shear stress.

Keywords: microalgae, raceway pond, sustainable energy, bioenergy, biofuel, computational fluid dynamics.
1: Introduction:

1.1: Energy: For Today and Future

Energy is inevitable for human life. It’s safe and accessible supply is not only important but crucial for the modern societies. Problems such as depletion of fossil fuel reserves, geopolitical & military conflicts indicate an unsustainable situation. Renewable energy is the key solution to the growing energy challenges. Renewable energy resources such as biomass, solar, wind is abundant, environmentally friendly and inexhaustible. Global warming and energy crisis are two major problems human being faces today. Population growth, fast industrialization, and increased use of fossil fuels contributes in the consumption of the available energy. The need for energy is rising with economic wealth (M. Asif, 2007) (J. Rupprecht, 2009). Worldwide supply of liquid fuels is completely dependent on petroleum. Due to present growth of prosperity and economics, petroleum will become more expensive as well as will cause political and military conflicts (C. Posten, 2009). Weather we notice it or not, the fact is energy is very important in our daily life as growth of every country depends on the ability to supply energy as per demand. The predicted expansion of world’s population is at least 9 billion by 2050, correlates increase of energy use globally to 812 quadrillion (10^{15}) kJ by 2035 from 533 quadrillion kJ in 2008 (J. N. Rogers, 2013).

1.2: Microalgae

Microalgae are the largest autotrophic microorganisms of plant life. Microalgae are known to synthesize and can rapidly accumulate higher amounts of lipids than terrestrial plants due to their high growth rates. Microalgae, recognized as one of the oldest living organisms. While the mechanism of photosynthesis in these microorganisms is similar to that of higher plants, they are generally more efficient converters of solar energy because of their simple cellular structure. In addition, Microalgae have more efficient access to water, CO₂, and other nutrients as they grow in aqueous suspension. Microalgae can be either autotrophic or heterotrophic. Microalgae can fix CO₂ efficiently from different sources, including the atmosphere, industrial exhaust gases, and soluble carbonate salts. Fixation of CO₂ from atmosphere is probably the most basic method to sink carbon, and relies on the mass transfer from the air to the microalgae in their aquatic growth environments during photosynthesis (F. A. K. Alparslan,). Microalgae use light and carbon dioxide (CO₂) and grow in aquatic environments to create biomass. They are basically a large and diverse group of simple, typically autotrophic organisms, ranging from unicellular to multi-cellular forms. They do not compete with food or other crops as they can be cultivated on arid and inhospitable land (J. Singh, 2016) (L. A. Ribeiro, 2015). Algae production on large commercial scale do not have a stringent requirement of environmental conditions and can be produced in aqueous suspensions where sufficient light and carbon dioxide is available.

1.3: Microalgae as Biomass

Algal biomass contains three main components: carbohydrates, proteins, and lipids/natural oils. Microalgae grow very quickly compared to terrestrial crops. Algae have a harvesting cycle of 1–10 days. They commonly double in size every 24 hours. They are capable to produce greater amounts of biomass per hectare than any kind of terrestrial crop. During the peak growth phase, some microalgae can double every 3.5 hours under optimal growth conditions (enough nutrients, sunlight etc.). Biofuels from algae have a high lipid density (15-300 times higher than traditional crops) as compared with other terrestrial crops (V. Andersson,
2012), (A. F. Claren, 2010), (Y. Chisti, 2008). In addition to producing biofuel, algae can also be considered for a variety of other uses, such as fertilizer, pollution control, and human nutrition. Considering increase in oil prices and climate changes, biofuels have become more important as potential alternative energy sources. Energy can be generated by burning biomass to generate heat and electricity. Some algae can even produce hydrogen gas under specialized growth conditions (W. Z. Johnson, 2009).

1.4: Micro algal Biofuel

Biofuels are the most important types of renewable energy. They can be categorized into first, second and third generation biofuels. Micro algal biofuels are thought as third generation biofuels. They are one of the most promising biofuel feed stock to solve global energy crisis and climate changes. The advantages of microalgae as a biofuel feed stock include potentially high photosynthesis efficiency and biomass yields, lack of competition for arable land and fresh water resource, and carbon mitigation (R. E. Reviews, 2015). An integrated system for a steam power plant and cogeneration processes with an algae cultivation system for bio fixation of CO₂ was proposed by Lira-Barragan et al with the purpose of reducing the overall CO₂ emissions and producing biodiesel that replaces fossil fuels used as liquid transportation fuels (L. F. Lira-barraga, 2015). Biodiesel and bioethanol are two most promising candidates for biofuels. All algae have the capacity to produce energy-rich oils. Oil content of some microalgae can exceed 80% of the dry weight. The most important aspect of microalgae is their ability to produce several different types of biofuels such as biodiesel, bioethanol, biohydrogen, and biogas. Interestingly, biofuels derived from algae provide a significant reduction in vehicular exhaust emissions versus standard fossil fuels (T. Taparia). Biodiesel from microalgae is a clean-burning alternative fuel, biodegradable, user-friendly, non-toxic, and free from Sulphur and odor. It has a higher flashpoint and greater lubricity as compared with traditional diesel fuel. It can be easily used by blending with petroleum fuel to create biofuel blend, rather than fully dependent on petroleum fuel (C. Hong, 2015), (C. N. Dasgupta , 2015).

1.5: Bioreactors for cultivation of Microalgae: closed photo-bioreactor and open raceway pond

Design of photo-bioreactor is deciding factor to control capital and operating cost for cultivation of microalgae on large scale. The two major bioreactor classes of microalgae growth systems are open ponds and closed reactors. The process parameters for growth of micro algal biomass can be controlled more efficiently in closed photo-bioreactors than the open ponds. But the cost of building (Capital) and operating such systems is too high for production of algal biomass especially for biofuels and bioenergy. Open ponds are more cost effective but they suffer from lesser control over growth parameter (Y. Chisti, 2008). The most common growth systems used for commercial purposes are open pond. Open ponds are frequently designed like raceway ponds (RWP), which feature paddle wheels and baffles to promote mixing. RWP are very popular as they are relatively inexpensive as compared to closed photo-bioreactor(J. G. G. Jonker, 2013), (A. Ozkan, 2012). RWP are further classified as convectional raceway pond and modified raceway pond. In convectional raceway pond mixing is carried out by using one or more paddlewheel (A. Darzins, 2010). Where modified raceway pond is operated using side entry axial flow impeller like Hydrofoil (HF) (Pub. No: WO/2013/186626, International Application No: PCT/IB2013/001224, 2013). Modified raceway pond is more energy efficient than the convectional raceway pond as power number of HF is considerably less than the paddle wheel (J. B. Joshi, 2011). HF impeller generates strong convective motion and lower turbulence.
compared to paddle wheels and pitched blade turbines (B. N. Murthy, 2008). Algae cells are sensitive to hydrodynamic stress. The concept of cell damage correlates interaction between free cells and isotropic turbulence eddies based on Kolmogorov’s theory. When the micro-eddies size is close to the cell dimension, cell damage is higher; therefore, one should adjust the fluid flow in the open pond to maintain length of micro-eddies larger than the cell size (H. Hadiyanto, 2013).

Generally, RWP consists of rectangular tank which is divided into two compartments by central baffles (Figure 1). In the present work, an attempt has been made to study modified design of RWP with respect ratio of Length (L) to Width (W) of channel of RWP. Computational Fluid Dynamics (CFD) analysis of RWP is carried out for optimization of L/W ratio and power consumption. CFD provides detailed flow pattern in the reactor which helps to understand the mixing patterns as well as optimization of configuration. Attempt has been made to study effect of various L/W ratio on important parameters like circulation velocity ($V_c$), Dead Zone, Power Consumption and Shear Stress which decide performance of RWP.

2: Pond Description:
The design and optimization of adequate bioreactors to cultivate microorganisms is a major step in the strategy that focus on converting scientific findings into a feasible product. Experiments were carried out in a pilot scale RWP. Volume of pilot scale RWP is 4500 liters. It consists of rectangular tank (Figure 1) with dimensions (325 cm (length) x 100 cm (depth) x 150 cm (width)). Rectangular tank is divided into two compartments of 65 cm width by a central baffle having dimensions of (195 cm (length) x 100 cm (depth) x 20 cm (width)). Tank consists of HF impeller having three blades of 45 cm diameter.

![Figure 1: Modified RWP](image)

3: Simulation:
The simulations were carried out in ANSYS CFX 14. The impeller baffle interaction was modeled using multiple reference frame approach. The inner zone was rotated at 125 rpm. Space discretization was carried out using second order upwind method. The simulations were carried out using steady state approach up to residuals of $10^{-4}$. SIMPLE algorithm was used for pressure velocity coupling. CFD simulations of raceway pond were carried out using standard
The set of equations for single phase flow can be found in Murthy and Joshi (2008) (B. N. Murthy, 2008).

The $k - \varepsilon$ turbulence model includes two transport equations to represent turbulence properties of the fluid flow. The first equation is for turbulent kinetic energy ($k$), and the second is for turbulent kinetic energy dissipation rate equation ($\varepsilon$) (H. Hadiyanto, 2013). These equations can be written as follows:

The turbulent kinetic energy ($k$) is calculated from its governing equations:

$$\frac{\partial}{\partial t} (\rho k) + \nabla (\rho u k) - \nabla \left( \left( \mu + \rho \frac{k^2}{\varepsilon} \right) \nabla k \right) = \frac{1}{2} \rho \left( \frac{k^2}{\varepsilon} \right) \left( \nabla u + (\nabla u)^T \right)^2 - \rho \varepsilon$$  \hspace{1cm} (1)

The rate of dissipation of turbulent kinetic energy is calculated from its governing equation:

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \nabla (\rho u \varepsilon) - \nabla \left( \left( \mu + \rho \frac{k^2}{\varepsilon} \right) \nabla \varepsilon \right) = \frac{1}{2} \rho \left( \frac{k^2}{\varepsilon} \right) \left( \nabla u + (\nabla u)^T \right)^2 - \rho \varepsilon_1$$  \hspace{1cm} (2)

The standard model parameters have been considered in present simulations such as $C_\mu = 0.09, C_{\varepsilon_1} = 1.44, C_{\varepsilon_2} = 1.92$.

The grid independence study has been carried out with three grid resolutions. CFD prediction for three different grid sizes of 0.7, 0.8 and 0.9 million were compared with results obtained by ultrasonic velocity profiler (UVP). In that comparison, it was observed that with an increase in number of grids from 0.8 to 0.9 million, improvement in CFD predictions is minimal. Thus, grid with 0.8 million cells was selected for further CFD simulations. Detail study of grid independency and validation of CFD prediction of U and W velocities with UVP results can be find out in same authors work as Computational studies of pilot scale high depth algal photo-bioreactor which is under review in Engineering in Life Science Journal (manuscript id: elsec.201600067).

3.1: Domain for Computational Study:

The CFD simulations were carried out for different L/W ratios using finite volume approach. Hydrodynamic investigation was carried out for three different L/W ratios such as 5, 10 and 15. Geometrical details and volumes of three designs are described in Table 1.

Table 1: Reactor Dimensions and Volumes of three different L/W Ratios.

|                      | Unit | L/W = 5 | L/W = 10 | L/W = 15 |
|----------------------|------|---------|----------|----------|
| Channel Length (L)   | (cm) | 325     | 650      | 975      |
| Channel Width (W)    | (cm) | 65      | 65       | 65       |
| Depth                | (cm) | 100     | 100      | 100      |
| Central Baffle Length| (cm) | 195     | 520      | 845      |
| Central Baffle Width  | (cm) | 20      | 20       | 20       |
| Volume               | (liter) | 4485  | 8710     | 12935    |
Channel Width, Depth and width of the central baffle were kept constant for all L/W ratios. It was found that volume of the tank increases with the length of the tank. For three different L/W ratio simulation were carried out to find velocity distribution, dead zone, power consumption and shear stress in RWP.

3.2: Velocity Distribution:
Velocity between 15 cm/s to 30 cm/s is commonly required velocity for cultivation of algae in commercial RWP. Type of flow such as Laminar or turbulent is depend upon velocity, density and viscosity of fluid. For higher velocities, flow will be turbulent which will enhance operational conditions of RWP. Uneven distribution of velocity can reduce efficiency of RWP and it was significantly found in lower L/W ratio. Velocity distribution study was carried out in different geometries using CFD simulations.

3.3: Dead Zone:
Dead zone is the volume of stagnant flow. It reduces the RWP’s volumetric capacity as well as the residence time of fluid. It causes uneven flow in the RWP and sedimentation of the algal cell (Hadiyanto et al., 2013). Lowest fluid velocity required to avoid settling of algae cell is 10 cm/s. To quantify dead zone Hadiyanto et.al used following formulae.

\[
\text{Dead Zone} = \frac{\text{Volume of tank with less than 10 cm/s velocity}}{\text{Total volume of tank}} \times 100 \tag{3}
\]

Presence of dead zone affects the productivity of microalgae in the RWP. Dead zone is generally form at the sharp turn (ends of central baffle) where possibilities of formation of boundary layer separation is maximum. Dead zones must be considered as an important parameter while designing RWP and it should be minimized.

3.4: Power Consumption:
Power consumption determines the operating cost of RWP. Power represents as energy consumed by the impeller for mixing and to keep biomass in suspension. It can be calculated by multiplying Torque (T) on the blades with angular velocity. Torque can be obtained by solving \( k - \varepsilon \) turbulence model for different geometries of RWP. Feasibility of production of biomass and biofuels from the cultivation of algae depends on power consumption. To make system feasible, designs should be modified in such a way that power consume as Watt / dry weight of biomass should be minimum.

3.4: Shear Stress:
The pond should be designed in order to accommodate a stress range that gives the optimal cell response. It is necessary to compute the area of RWP where value of shear stress is more than optimal value. The concept of cell damage correlates interaction between free cells and isotropic turbulence eddies based on Kolmogorov’s theory. When the micro-eddies size is close to the cell dimension, cell damage is higher; therefore the fluid flow should be controlled in the photo-bioreactor to maintain length of micro-eddies larger than the cell size (F. Garci, 2000).
4: Results of CFD Simulation and Discussions:
In order to evaluate optimum design of RWP with respect to Length (L) to width (W) ratio, flow characteristics of three different L/W ratios such as 5, 10 and 15 were investigated.

4.1 Velocity Distribution:
Figure 2 shows the results of the simulation under constant agitation speed (125 rotation per minute) for three different L/W ratios. Contour plot of velocity shows liquid flows along the channel and take 180° turns at the bends. As per the contour plot, Figure 2 it was clear that uneven distribution of velocity was more significant in lower L/W ratio and by increasing L/W ratio more uniformity of velocity can be maintained. Minimum required velocity in commercial cultivation plant of algae is 15 cm/s.

![Velocity Contour](image)

Figure 2: Velocity Contour

4.2 Dead Zone:
Dead zone for all three L/W of RWP were shown in figure 3. Figure 3 indicates decrease in dead zone with the increase in L/W ratio. L/W, 15 shows minimum dead zone and L/W, 5
shows maximum dead zone. Dead zones were calculated by equation no 3 where volume of region having velocity less than 10 cm/s is evaluated by CFD code.

![Figure 3: Dead Zone](image)

### 4.3 Power Consumption:

Power consumption for different L/W ratios was shown in the Table 2. Ratio of power to volume decreases with increasing L/W ratio.

**Table 2: Power Consumption**

| Sr No | L/W | Volume m³ | Torque N m | Power Watt | Watt/ m³ |
|-------|-----|-----------|------------|------------|----------|
| 01    | 5   | 4.4       | 2.88       | 47         | 10.7     |
| 02    | 10  | 8.7       | 4.53       | 71         | 8.2      |
| 03    | 15  | 12.9      | 5.71       | 75         | 5.8      |

As per the Table 2, Power required for constant agitation speed (125 rotation per minute) in the case of L/W, 15 was minimum where for L/W, 5 it was maximum. Therefore higher L/W design is more energy efficient. Calculated power consumption for various L/W was shown in Figure 4.
4.4: Shear Stress:

Size of micro-eddies can be find out by using formula given by (H. Hadiyanto, 2013) Hadiyanto et al.

\[
\lambda = \left( \frac{\eta}{\rho} \right)^{0.75} \varepsilon^{-0.25}
\]  

(4)

Where

\begin{align*}
\lambda & = \text{Size of micro-eddy, m} \\
\eta & = \text{Dynamic viscosity, Pa.s} \\
\rho & = \text{Density kg m}^{-3} \\
\varepsilon & = \text{Rate of energy dissipation, W kg}^{-1}
\end{align*}

Figure 5 indicates size of micro-eddies for all designs in micro meter. Size of algal cell is approximately 100 µm, so to minimize damage to algal cell, RWP should be designed to maintain size of micro-eddies more than 100 µm. In all modification size of micro-eddy was found to be more than 100 µm. In, L/W = 10, length of micro-eddies is found to be 114 µm which is slightly greater than 100 µm.
Figure 6 shows magnitudes of shear stress in all three designs. Shear stress can be formulated using $k - \varepsilon$ turbulence model. From the figure 6, it was clear that, shear stress decreased with increase in $L/W$ ratio. Maximum shear stress is observed in $L/W$, 5 where it decreases with increasing $L/W$ ratio.

![Figure 6: Shear Stress, Pa](image)

5. Conclusion:

The CFD model was developed to study hydrodynamics of modified RWP with different $L/W$ ratios. An increase in $L/W$ ratios showed increase in uniformity of velocity distribution and thus dead zone in the RWP photo-bioreactor was also decreased with increase in $L/W$ ratio. The power consumption per unit volume was lower when $L/W$ ratio was increased from 5 to 15. Higher ratios of $L/W$, RWP photo-bioreactor design were more energy efficient. The modified RWP design enabled algae production for liquid depth of 1 m. Further studies involving optimization of bend geometry, sparger design, sparger location to improve the performance of modified RWP design are ongoing.

Acknowledgements

This work was supported by the Department of Biotechnology, Ministry of Science and Technology, Government of India (No. BT/PR13796/PBD/26/139/2010). Authors, Mr. Shekhar S Sawant and Mr. Bhavesh Ghajbhiye would like to acknowledge the fellowship support from UGC and DAE-ICT Centre, respectively.

Nomenclature

- $C_\mu$: Constant in $k-\varepsilon$ turbulence model
- $C_{\varepsilon 1}$: Model parameter in dissipation rate of turbulent kinetic energy in Equation 2
- $C_{\varepsilon 2}$: Model parameter in dissipation rate of turbulent kinetic energy in Equation 2
- $k$: Turbulent kinetic energy ($m^2/s^2$)
- $L$: Channel length (m)
- $W$: Channel width (m)
- $m$: Mass (kg)
- $N_P$: Power Number (-)
Pressure (N/m²)
Power (W)
Time (s)
Torque (N.m)
Velocity vector (m/s)
Mean velocity (m/s)

Turbulent kinetic energy dissipation rate (m²/s³)
Effective viscosity (Pa.s)
Turbulent viscosity (Pa.s)
Molecular viscosity (Pa.s)
Kinematic Viscosity (m²/s)
Density (kg/m³)

Computational Fluid Dynamics
Hydrofoil
Raceway Pond
Ultrasonic Velocity Profiler

"Microalgae for renewable energy: biodiesel production and other practies", The 4 th International Symposium of Sustainable Development.
"Integrated algae cultivation for municipal wastewater treatment and biofuels production in industrial clusters", Energy Forum 2011, 1–8. Retrieved from https://ases.conference-services.net/resources/252/2859/pdf/SOLAR2012_0347_full paper.pdf
"Energy supply, its demand and security issues for developed and emerging economies", Renewable and Sustainable Energy Reviews, 11(7), 1388–1413. https://doi.org/10.1016/j.rser.2005.12.004
"Biodiesel from microalgae beats bioethanol. Trends in Biotechnology", 126–131. https://doi.org/10.1016/j.tibtech.2007.12.002
"Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks", Environmental Science & Technology, 44(5), 1813–1819. https://doi.org/10.1021/es902838n
"Current Status and Potential for Algal Biofuels Production", National Renewable Energy Laboratory, A report to IEA BioEnergy Task 39, Report T-39-T2, 6 August,2010 .
"Dual uses of microalgal biomass : An integrative approach for biohydrogen and biodiesel production". Applied Energy, 146, 202–208. https://doi.org/10.1016/j.apenergy.2015.01.070
F. Garcia Camacho, A. Contreas Gomez, T. Mazzuca Sobczuk, E. Molina Grima, 2000. "Effects of mechanical and hydrodynamic stress in agitated, sparged cultures of Porphyridium cruentum", Process Biochemistry, Volume 35, Issue 9, Pages 1045–1050.

H. Hadiyanto, S. Elmore, T. Van Gerven, A. Stankiewicz, 2013. "Hydrodynamic evaluations in high rate algae pond (HRAP) design". Chemical Engineering Journal, 217, 231–239. https://doi.org/10.1016/j.cej.2012.12.015

C. H. Tang, W. Y. Cheah, T. C. Lian, S. P. Loke, J. C. Juan, J. S. Chang, 2015. "Algae Cultivation in Wastewater for Biodiesel – A Review", 45, 1393–1398. https://doi.org/10.3303/CET1545233

W. Z. Johnson, 2009. "Microalgae as a Feedstock for Biofuel Production". Virginia Cooperative Extension, 442–486. https://doi.org/10.1016/j.nbt.2009.06.630

J. G. G. Jonker, A. P. C. Faaij, 2013. "Techno-economic assessment of micro-algae as feedstock for renewable bio-energy production". Applied Energy, 102, 461–475. https://doi.org/10.1016/j.apenergy.2012.07.053

J. B. Joshi, N. K. Nere, C. V. Rane, B. N. Murthy, C. S. Mathpati, A. W. Patwardhan, V. V. Ranade, 2011. "CFD simulation of stirred tanks: Comparison of turbulence models (Part II: Axial flow impellers, multiple impellers and multiphase dispersions)". Canadian Journal of Chemical Engineering, 89(August), 754–816. https://doi.org/10.1002/cjce.20465

A.M. Lali, R.A. Pandit, P. Gunjan, C.S. Mathpati, S.P. Gangal, C.P. Vira, J.A. Palkar, S.D. Patil, S. P. Gaikwad, 2013. Pub. No: WO/2013/186626, International Application No: PCT/IB2013/001224. India.

L. F. Lira-barraga, F. A. Jose, M. M. El-halwagi, 2015. "Reduction of greenhouse gas emissions from steam power plants through optimal integration with algae and cogeneration systems", 2401–2415. https://doi.org/10.1007/s10098-015-0982-1

B. N. Murthy, J. B. Joshi, 2008. "Assessment of standard k - ε, RSM and LES turbulence models in a baffled stirred vessel agitated by various impeller designs". Chemical Engineering Science, 63(22), 5468–5495. https://doi.org/10.1016/j.ces.2008.06.019

A. Ozkan, K. Kinney, L. Katz, H. Berberoglu, 2012. "Reduction of water and energy requirement of algae cultivation using an algae biofilm photobioreactor". Bioresource Technology, 114, 542–548. https://doi.org/10.1016/j.biortech.2012.03.055

C. Posten, G. Schaub, 2009. "Microalgae and terrestrial biomass as source for fuels-A process view", Journal of Biotechnology, 142(1), 64–69. https://doi.org/10.1016/j.jbiotec.2009.03.015

R. E. Reviews, 2015. "Biogas production from algal biomass: A review". https://doi.org/10.1016/j.jrser.2014.11.052

L. A. Ribeiro, P. Pereira, T. M. Mata, 2015. "Prospects of using microalgae for biofuels production : Results of a Delphi study", 75, 799–804. https://doi.org/10.1016/j.ij.cog.2014.10.065

J. N. Rogers, J. N. Rosenberg, B. J. Guzman,, V. H. Oh, L. E. Mimbela, A. Ghassemi, M. D. Donohue, 2013. "A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales". Algal Research, 4, 76–88. https://doi.org/10.1016/j.algal.2013.11.007

J. Rupprecht, 2009. "From systems biology to fuel-Chlamydomonas reinhardtii as a model for a systems biology approach to improve biohydrogen production". Journal of Biotechnology, 142(1), 10–20. https://doi.org/10.1016/j.jbiotec.2009.02.008

J. Singh, S. Gu, 2016. "Commercialization potential of microalgae for biofuels production".
Renew Sust Energ Rev.  https://doi.org/10.1016/j.rser.2010.06.014
T. Taparia, M. Mvss, R. Mehrotra, P. Shukla. "Developments and challenges in biodiesel production from microalgae: A review", 1–12. https://doi.org/10.1002/bab.1412