

## Review on Microalgae Cultivation Using Wastewater for Biofuel Production<sup>•</sup>

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### Abstract

The integrations of wastewater treatment and microalgae-based biofuel have attended considerable. This paper describes the overview of microalgae in terms of biofuel productivity, cultivation of microalgae, harvesting microalgae and method for converting microalgae biomass to biofuel productions. The species of microalgae mostly used for cultivating in the wastewater to produce biofuel are presented. There are two major systems for cultivating microalgae: 1) opened system (raceway, circular and unmixed pond) and 2) closed system (photobioreactor, tubular and flat plate). The suitable selection of harvesting method is very critical because it can reduce the overall cost. Microalgae can be harvested by flocculation, flotation, filtration and gravity, and centrifugal sedimentation. In the present paper, the energy conversion process is explained and can be classified into thermochemical and biochemical conversions. Microalgae biomass can be used in a wide range of applications, including fertilizers, nutraceuticals, cosmetics, wastewater treatment, fish and animal feeds, and biofuels. Furthermore, microalgae biomass can also be converted into bio-oil, ethanol, methane, biodiesel and syngas. The selection of the conversion process depends on the species of microalgae, the final productivity and the possible economic factor. Most researchers are investigated the sustainable energy source as an alternative to fossil fuels. The microalgae are identified as the best feedstock to be convert into a biofuel production. The microalgae cultivation does not need a large land, possesses a high growth rate, and enhances the amount of lipid for a biofuel production. There have been few studies involving microalgae biofuel production using industrial wastewater. Finally, the future directions for integrated wastewater treatment and microalgae biofuel production are suggested.

**Keywords:** Microalgae, cultivation system, harvesting system, energy conversion process, wastewater.

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## 1. Introduction

In the 21<sup>st</sup> century, there are two major issues for human society in the world, 1) energy and 2) water quality [1]. Water scarcity is a growing international concern [2]. When the water sources are contaminated from pollutants making the water unsuitable for use [3]. For the energy issue, the gap between the requirement and the supply of energy is growing wider [4]. The 80% of global energy demand which produces from fossil fuels. Fossil fuels as energy sources are unsustainable due to the limited resources [5]. Using fossil fuels cause global warming and greenhouse effect gases. Therefore,

the renewable clean energy is required as a fossil fuel replacement [6]. Bioenergy is a key role to meet the global challenges of clean and sustainable energy requirement [4].

The interest in a biological wastewater treatment and the biomass conversion from waste to bioenergy production, is increasing. Phytoremediation is a common wastewater treatment using macro algae and microalgae for the removal pollutants such as organic and inorganic [2]. Fig. 1 shows the concept of using microalgae for wastewater treatment and bioenergy production.

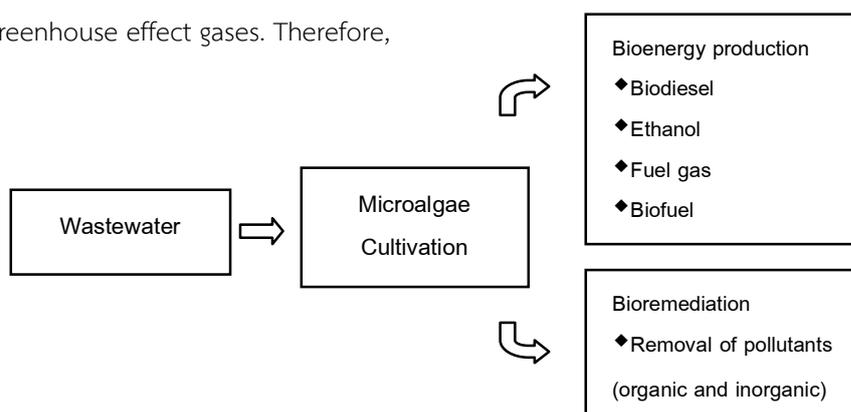


Fig. 1 The concept about using microalgae for wastewater treatment and bioenergy production (adapted from Ma et al. [7])

Microalgae can produce the lipid production but they require the suitable physical and chemical conditions such as temperature, light and other conditions in the culture medium to increase the overall lipid yield. The microalgae have increased its attention in recent years [8]. The advantages of using microalgae as a source of biomass for bioenergy production are: fast growth, short time for generation, high oil content, not much land requirements, synergy with CO<sub>2</sub> biofixation and wastewater

bioremediation that can use nutrients in wastewater to grow [7-8]. Moreover, biomass from microalgae can be used in many applications, such as fertilizers, cosmetics, biofuels, fish and animal feeds [7].

There are many studies on bioenergy productions from microalgae. Thus, the bioenergy from microalgae is not new, and such method can reduce the global warming and greenhouse effect gases. Most of the studies focus on cultivation system, collection of

microalgae, genetic engineering and system and resource analysis [10]. This paper presents an overall review on microalgae cultivation technology and the method for converting the microalgae to bioenergy production.

## 2. Microalgae for bioenergy production

There are about 100,000 species of algae which 35,000 species are described before [11]. Microalgae are unicellular and autotrophic organisms using sunlight, water and CO<sub>2</sub> from the atmosphere to grow [11-14]. Diameter of microalgae is usually smaller than 2 mm and they are either single cellular or multicellular. The microalgae can live in several environments such as freshwater, marine water and wastewater, depending on the species of microalgae [15]. The microalgae are both of autotrophic and heterotrophic. Non-photosynthesis requires an external source of organic compounds as nutrients sources. Autotrophic microalgae convert solar radiation and CO<sub>2</sub> absorbed by chloroplasts, to adenosine triphosphate (ATP) and O<sub>2</sub> [16].

The microalgae produce biomass that can be converted to renewable fuel such as ethanol, biodiesel, bio-oil and charcoal [17].

The advantages of microalgae utilization as the resources of biomass include [6], [17]:

- Microalgae are an efficient biological system for harvesting the solar energy to produce the organic compound;
- Microalgae can produce high concentrations of proteins, lipids, pigments and carbohydrates;
- Microalgae cell is a simple cell division cycle;

- Microalgae can grow in several environments;

- Biomass from microalgae can easily be adapted to various options of operational or technological skills;

- Microalgae have very short harvesting life.

Microalgae are rich in oil [6]. Eighty percentages of biomass from microalgae can produce oil [18-19]. The Aquatic Species Program (ASP) considered three main options of biomass from microalgae that can be converted to fuel production [6], [20], including biodiesel, ethanol and methane. The last option is the direct combustion of the biomass from the microalgae for production of electricity [6].

Microalgae cultivation on the wastewater had developed from the microalgae in wastewater treatment [21]. In 1950, USA started to study how to use the microalgae for wastewater treatment [22]. The Wastewater is unique in chemical and physical properties in comparison with the fresh water and the marine water [21]. The microalgae have some advantages because of their structures and metabolisms in their cells [1]. The microalgae can use organic and inorganic nutrients from the wastewater to produce biomass that can be used as raw material for biofuel productions. The wastewater is suitable for microalgae cultivation due to the nutrient content that can support the microalgae growth [23]. The nutrients exist in wastewater include nitrate, ammonia, organic nitrogen, phosphate, urea and trace minerals such as Mg, K, Fe, Ca, Cu and Mn. Many researches indicated that ammonium had effect on microalgae as much as concentration. The microalgae require nitrogen source for their

growth. One thing to be concern is nitrogen source is not easy to manage in wastewater. Table 1 shows the summary of the studies on species of microalgae that can be cultivated in the wastewater. Therefore, using wastewater as a resource for microalgae cultivation could serve dual purposes: 1) improving microalgae biomass production and 2) improving wastewater treatment efficiency.

### 3. Microalgae cultivation system

There are many systems for cultivating the microalgae. The microalgae can be cultivated in open systems including raceway, circular, inclined and unmixed pond or in closed system including photobioreactor, tubular, fermenter-type, vertical, flat plate, flat tank, bubble column, serpentine, annular and internally illuminated photobioreactors [34].

The opened systems are very simple and usually established as shallow ponds by the walls for microalgae growth. Water and nutrients can easily be added by runoff water [9], [35] or by wastewater from the point sources. Water, nutrients and CO<sub>2</sub> are continuously fed to the ponds. The opened systems have received a lot of attention for the commercial cultivation because of its ease of set-up process [34].

The closed system cultivation has less contamination and easy to control [34]. The closed system can be an indoor with artificial light or outdoor with direct sunlight [9].

#### 3.1 Opened pond system

Opened pond systems are commonly used for cultivation of microalgae at the commercial

level [1]. The cost of a system that uses an opened pond of large-scale microalgae for producing microalgae biomass, is lower than closed system. Raceway ponds commonly use because of their simple set-up process [36]. The raceway ponds are operated with the aid of paddle wheels to make the water flow continuously [34]. The raceway ponds can increase the productivity by improving the CO<sub>2</sub> mass transfer [37]. High rate algae pond (HRAP) has been used in the opened pond system for a wastewater treatment. Most researches have reported that the opened pond does not need a lot of maintenance or cost. Nevertheless, the opened ponds need some maintenance and easy for contamination. Other uncontrollable factors are intensity, sunlight and temperature. High biomass productivity cannot be achieved from these systems. The number of species that can be cultivated in opened ponds include *Chlorella sp.*, *Dunaliella sp.* and *Spirulina sp.* [38].

#### 3.2 Closed system

The limitations of opened ponds can be adjusted by photobioreactors, as an alternative way to overcome the low productivity and contamination [16], [38]. The closed system has many benefits including high microalgae biomass production, the environmental issue management, and another microalgae species contamination prevention. The popular types of photobioreactor are tubular, column and flat plate. The most popular reactor is the vertical tubular reactor with has high surface, low cost, low shear forces, high CO<sub>2</sub> use efficiency and ability to use sunlight [34].

**Table 1** Summary of microalgae that cultivate in wastewater.

<i>Species</i>	<i>Wastewater</i>	<i>Characteristics of wastewater</i>	<i>Biomass productivity (mgL<sup>-1</sup>d<sup>-1</sup>)</i>	<i>Ref.</i>
<i>Botryococcus braunii</i>	Piggery	284 mgL <sup>-1</sup> COD 836 mgL <sup>-1</sup> TN 788 mgL <sup>-1</sup> NO <sub>3</sub> <sup>-</sup>	1.80	[24]
	Secondary treated sewage	7.67 mgL <sup>-1</sup> NO <sub>3</sub> <sup>-</sup> 0.19 mgL <sup>-1</sup> NO <sub>2</sub> <sup>-</sup>	35	[25]
<i>Chlamydomonas reinhardtii</i>	Municipal (centrate)	128.6 mgL <sup>-1</sup> TN 120.6 mgL <sup>-1</sup> TP	820	[26]
	Municipal wastewater	128 mgL <sup>-1</sup> TKN 67 mgL <sup>-1</sup> NH <sub>3</sub> 120 mgL <sup>-1</sup> TP	2	[27]
<i>Chlorella sp.</i>	Centrate, municipal wastewater	85.9 mgL <sup>-1</sup> NH <sub>4</sub> <sup>+</sup> 132.3 mgL <sup>-1</sup> TN 215.1 mgL <sup>-1</sup> TP	920	[28]
	Animal wastewater	10-400 mgL <sup>-1</sup> TN 0.7-4.4 mgL <sup>-1</sup> TP	6.83	[29]
	Municipal wastewater	132.3 mgL <sup>-1</sup> TN 215.1 mgL <sup>-1</sup> TP 2389.5 mgL <sup>-1</sup> COD	0.92	[28]
<i>Chlorella vulgaris</i>	Dairy manures	1008 mgL <sup>-1</sup> NH <sub>4</sub> <sup>+</sup> 180 mgL <sup>-1</sup> TP 17820 mgL <sup>-1</sup> COD	80-152	[30]
	Dried anaerobic sludge	1.6-9.8 mgL <sup>-1</sup> TN 1.1-3.0 mgL <sup>-1</sup> TP	39-195	[31]
<i>Consortia microalgae</i>	Carpet mill	2.83 mgL <sup>-1</sup> NO <sub>3</sub> <sup>-</sup> 4.8 mgL <sup>-1</sup> PO <sub>4</sub> <sup>-3</sup>	41	[32]
<i>Scenedesmus acutus</i>	Municipal wastewater after aerobic treatment	5.3-97.6 mgL <sup>-1</sup> NO <sub>3</sub> <sup>-</sup> 27.7-207.2 mgL <sup>-1</sup> NH <sub>4</sub> <sup>+</sup> 7.3-122.1 mgL <sup>-1</sup> PO <sub>4</sub> <sup>-3</sup> 273.5-782.8 mgL <sup>-1</sup> COD	73.7	[33]

**Table 2** The comparison of open ponds and photobioreactors [1], [16], [39-40], [42].

System	Advantages	Limitations
Raceway pond	<ul style="list-style-type: none"> <li>-Easy set up</li> <li>-Easy maintenance</li> <li>-Low capital and operation costs</li> <li>-Easy cleaning</li> <li>-Low energy input</li> <li>-Utilized non-agricultural land</li> </ul>	<ul style="list-style-type: none"> <li>-Poor biomass productivity</li> <li>-Large area of land required</li> <li>-Easy contaminated</li> <li>-Limited to a few strains of algae</li> <li>-Poor mixing, light and CO<sub>2</sub> utilization</li> <li>-Loss of water</li> <li>-Grow slower</li> </ul>
Tubular photobioreactor	<ul style="list-style-type: none"> <li>-Good biomass productivity</li> <li>-Suitable for outdoor cultures</li> <li>-Large illumination surface area</li> <li>-Single species culture</li> <li>-Easy to operate</li> <li>-Short time for harvesting</li> <li>-High surface to volume ratio</li> </ul>	<ul style="list-style-type: none"> <li>-Large are of land required</li> <li>-Gradients of pH, dissolved oxygen and CO<sub>2</sub> along the tubes</li> <li>-Required supplied of air to operate by using airlift pumps</li> <li>-High concentration of O<sub>2</sub> will inhabit photosynthesis</li> <li>-Fouling</li> </ul>
Flat plate photobioreactor	<ul style="list-style-type: none"> <li>-Relatively cheap</li> <li>-High biomass productivity</li> <li>-Good for microalgae immobilization</li> <li>-Easy cleaning</li> <li>-Good light path</li> <li>-Large illumination surface area</li> <li>-Low O<sub>2</sub> accumulation</li> <li>-Low contamination</li> <li>-Good for indoor and outdoor cultures</li> </ul>	<ul style="list-style-type: none"> <li>-Difficult large scale-up</li> <li>-Difficult control for temperature</li> <li>-Some degree of wall growth</li> <li>-Difficult control for CO<sub>2</sub></li> <li>-Photo-inhibition may occurs</li> </ul>

Microalgae in photobioreactor are cultivated in suspension, and the systems are closed while the water can be circulated by pumps [39]. Photobioreactors consist of an array of plastic tubes or straight glass [16], [40]. The tubular array captures the sunlight. Gas liquid mass

transfer is very important feature for the photobioreactors. The microalgae in photobioreactors can be re-circulated by pump and air lift system. Thus the CO<sub>2</sub> and O<sub>2</sub> can be exchanged between the aeration gas and the liquid medium [16]. Flat plate photobioreactors

can achieve high cell densities due to the large surface area exposed for the solar capture [16], [38]. The flat plate reactors are more suitable than the tubular reactors for large scale [16]. A larger reactor of species can be cultivated in photobioreactors [41]. Table 2 shows the comparisons of opened ponds and photobioreactors. The opened pond system causes lower productivity of microalgae biomass than that of the closed pond system, due to some limitation factors such as lacking of carbon dioxide, decreasing of evaporation, incapable mixing, suitable temperature for growth and light intensity limitation [16].

#### 4. Microalgae harvesting systems

Harvesting is the serial progress of water removal from microalgae cultivation and supports the different of downstream processes. The downstream process is dewatering, drying and lipids extraction. It is very important to choose a suitable harvesting method to reduce the overall cost [42]. The harvesting methods always depend on the species of microalgae such as size, density of microalgae. Normally, the microalgae harvesting is a two-stage process. The first stage is a bulk harvesting to separate the biomass from the bulk suspension such as flocculation, flotation or gravity sedimentation. The second stage is thickening to concentrate the slurry through techniques like centrifugation, filtration and ultrasonic aggregation [16], [42-43].

##### 4.1 Screening

Screening is the first process for wastewater treatment plant. Microalgae harvesting also uses the screening. The principle of screening

involves introducing microalgae biomass onto a screen of given aperture size. The aim of screening is to take the particle or microalgae biomass and put into the space of screening medium. The efficiency of screening depends on the spacing between the screen opening hole and the microalgae particle size. Two screening devices of for harvesting microalgae include microstrainer and vibrating screen, a common screening device.

##### 4.2 Flocculation

Microalgae generally have negative charge at their microalgae cell surface that prevents self-aggregate. Flocculation is used for microalgae suspension. Substance is combined with the negative charge of microalgae cell surface. Adding of a flocculants into the medium, the metal salts such as ferric chloride, aluminum sulfate and ferric sulfate from flocculants act to displace the charge and allow the aggregation of microalgae, resulting in a better sedimentation [8]. Alum and ferric chloride are flocculants that used for harvest microalgae [44]. Use of chemical flocculants is expensive for a large operation [6], [8]. Autoflocculation, is the spontaneous aggregation of microalgae, can occur by limitation of carbon or certain abiotic factors [8], [45]. The flocculation process requires lower energy than other methods, such as filtration, flotation, gravity sedimentation, and centrifugal sedimentation.

##### 4.3 Filtration

Filtration is a commonly used for separating of liquid and solid phases. It is a flowing of microalgae suspension that passes through filter equipment using suction pump. The microalgae pass through other filtration process for

prevention of pore blocking or membrane fouling. The filtration is suitable for large colony or large cell of microalgae. The filtration is separated into 0.1 to 10 microns. There are many types of filtration process such as vibrating screen, belt filter, vacuum drum, microfiltration, vacuum filtration, dead end filtration, and pressure filtration [46]. The filtration tends to be costly, energy intensive, fouling and pumping [45].

#### *4.4 Flotation*

Flotation is based on the trapping of microalgae cells using dispersed bubbles. It depends on air or gas foam. Air and particle are attached each other and then push them to the top of water, they are harvested using a skimming equipment. Some cells of microalgae float the surface water [16]. The flotation aims to enhance the solid loading, how many percent that the solid is floated, and make the product be clearly. Flotation has many different kinds such as dissolved air flotation, electro flotation, dispersed flotation and ozone flotation.

#### *4.5 Gravity sedimentation*

Gravity sedimentation is commonly used for harvesting microalgae biomass. It is a technique to separate liquid and solid to get clear water and take a feed suspension into slurry in high concentration. The gravity sedimentation is suitable for high density and large size of microalgae [47]. However, it may take more time to setting them down for small cell.

#### *4.6 Centrifugal sedimentation*

Centrifugal sedimentation is the way to separate to liquids that cannot mix together. It is the most rapid and reliable method of recovering suspended microalgae [48]. The

centrifugal sedimentation is similar with sedimentation tank but the particle suspension is forced using centrifugation for their division which is greater than gravity force. Two important factors for centrifugal sedimentation are size and density of microalgae. There are many kinds of centrifugal sedimentation such as solid bowl decanter, hydro cyclone, nozzle type, solid ejecting disc, imperforate, multi-chamber, tubular centrifuge and decanter centrifugation. This process is rapid and energy intensive. The centrifugal sedimentation has a high energy cost and a high maintenance requirement [16], [42].

## **5. Energy conversion process**

The energy conversion processes from microalgae biomass can be classified into thermochemical and biochemical conversions [48-49]. The thermochemical conversions include gasification, pyrolysis, liquefaction, direct combustion, and hydrogenation. The biochemical conversions include fermentation, anaerobic digestion and transesterification. Fig 2 shows the converting microalgae biomass process. The microalgae biomass can be converted into bio-oil, ethanol, methane, biodiesel, syngas, hydrogen and electricity. The selection of conversion process is determined by the species of microalgae to biomass, final productivity that needed and the possible economic factor [16], [42].

### *5.1 Thermochemical conversion*

#### *5.1.1 Gasification*

Gasification can be used for converting microalgae biomass into syngas and fuel gas by partial oxidation with air at high temperatures ranging from 800 to 1000 °C [50]. Syngas can

produce a wide variety of potential feedstock [16]. The syngas from this process is a low calorific gas and it can be used directly as a fuel for engines and turbines [16], [42], [51].

5.1.2 Pyrolysis

Pyrolysis is an energy process for converting microalgae biomass by heating at temperature

ranging from 350 to 700 °C in the absence of air or oxygen become bio-oil, syngas and charcoal [52]. There are 3 classes of pyrolysis process include flash pyrolysis, fast pyrolysis and conventional pyrolysis [42]. The fast pyrolysis can directly produce a liquid fuel [53].

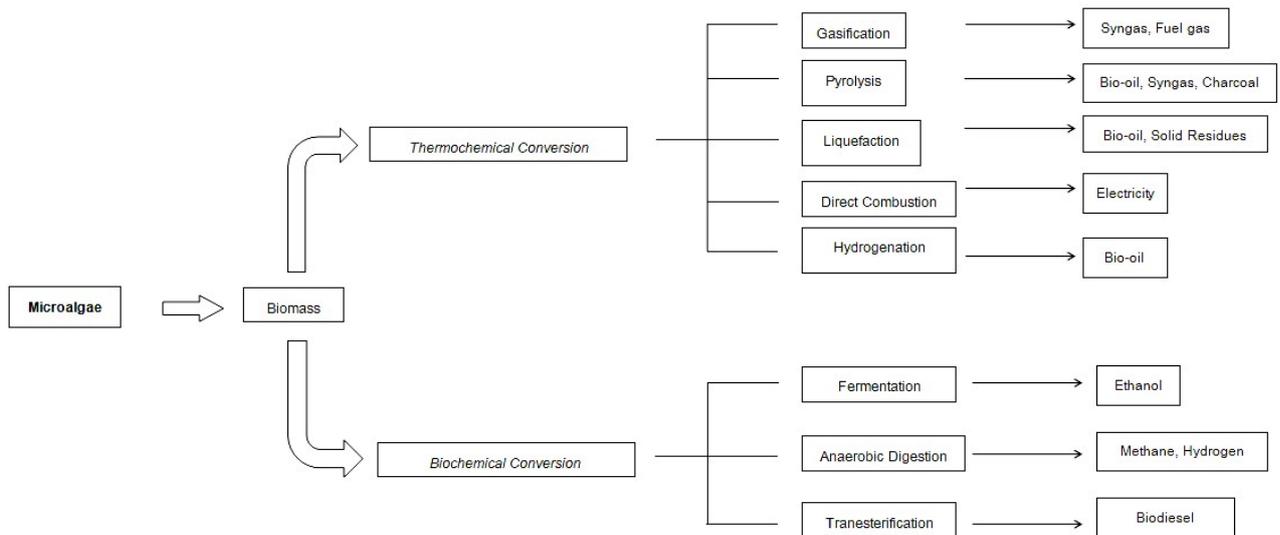


Fig. 2 The energy conversion process from microalgae biomass [6], [16], [42]

5.1.3 Liquefaction

Liquefaction is an energy process for converting the wet microalgae biomass to biofuels [54]. The liquefaction has a temperature ranging from 200 to 350 °C at high pressure (5-20 MPa) with catalyst convert to bio-oil and hydrogen [44], [52]. The liquefaction is a practical option for the conversion of wet microalgae biomass to bioenergy.

5.1.4 Direct combustion

The microalgae biomass is burnt in the air to convert the chemical energy that stored in microalgae biomass into hot gases with temperature ranging from 800 to 1,000 °C [42], [52]. Direct combustion is suitable for microalgae

biomass which has the moisture content less than 50% dry weight [42]. Limitations of direct combustion are the requirement of pretreatment such as grinding, chopping and drying and some extra cost [16], [52].

5.1.5 Hydrogenation

Hydrogenation is a process that adds the hydrogen atoms to double bonds of a molecule by catalyst [55]. Microalgae hydrogenation is performed by using an autoclave at high temperature and using the pressure conditions of catalyst and solvent [6].

## 5.2 Biochemical conversion

### 5.2.1 Fermentation

Fermentation is an energy process for converting microalgae biomass, containing starch, cellulose and sugar to ethanol. The fermentation is commonly used in a large scale. The first step is to extract the starch from the microalgae cell and to convert the starch by enzymes into sugars. Then, sugars are converted to ethanol by yeast. The distillation process is used to purify the ethanol by removing the water and impurities.

### 5.2.2 Anaerobic digestion

Anaerobic digestion is an energy process for converting organic waste to a biogas, consisting of methane and carbon dioxide. Methane and carbon dioxide from this process can be used directly as cooking fuel, gas-quality bio-methane and generating power gas engines [42]. The anaerobic digestion is suitable for high moisture material such as wet microalgae biomass [16].

### 5.2.3 Transesterification

Transesterification is a process of exchanging an ester compound with another alcohol [6]. The reaction of transesterification is fat or oil conversion using alcohol into ester and glycerol. The productivity of transesterification is biodiesel.

## 6. Conclusions

The microalgae have attended considerable in recent year. The cultivation of microalgae can be used in wastewater treatment and renewable energy. The advantages of using microalgae are fast growth, high oil content and synergy with CO<sub>2</sub> biofixation. For cultivating microalgae and energy conversion process, there are many

systems that still required a high investment in comparison with the conventional diesel from fossil or conventional wastewater treatment. The new approach involves several industrial wastewaters to attain the optimum technology for improvement microalgae biomass production. This topic is very challenging for improving the alternative energy that can be used and reduced the use of fossil fuels. Future research in the directions discussed in this review will ensure sustainable microalgae for biofuel production using industrial wastewater as a resource.

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## References

- [1] E.-S., Salama, M. B., Kurade, R. A. I., Abou-Shanab, M. M., El-Dalatony, I. S., Yang, B., Min and B. H., Jeon, "Recent progress in microalgae biomass production coupled with wastewater treatment for biofuel generation," *Renewable and Sustainable Energy Reviews*, 79, pp. 1189-1211, 2017.
- [2] S. P., Cuellar-Bermudez, G. S., Aleman-Nava, R., Chandra, J. S., Garcia-Perez, J. R., Contreras-Angulo, G., Markou, K., Muylaert, B. E., Rittmann and R, Parra-Saldivar, "Nutrients utilization and contaminants removal," A review of two approaches of algae and cyanobacteria in wastewater. *Algal Research*, 24, pp. 438-449, 2017.

- [3] M, Falkenmark and J, Rockstrom, "Balancing water for humans and nature: the new approach in ecohydrology," Earthscan, 2004.
- [4] K., Kumar, S., Ghosh, I., Angelidaki, S. L., Holdt, D.B., Karakashev, M. A., Morales and D, Das, "Recent developments on biofuels production from microalgae and macroalgae," *Renewable and Sustainable Energy Reviews*, 65, pp. 235-249, 2016.
- [5] A., Ahmad, A., Buang and A. H., Bhat, "Renewable and sustainable bioenergy production from microalgae co-cultivation with palm oil mill effluent (POME): A review," *Renewable and Sustainable Energy Reviews*, 69, pp. 214-234, 2016.
- [6] S., Amin, "Review on biofuel oil and gas production processes from microalgae," *Energy Conversion and Management*, 50, pp. 1834-1840, 2009.
- [7] X., Ma, W., Zhou, Z., Fu, Y., Cheng, M., Min, Y., Liu, Y., Zhang, P., Chen and R., Ruan, "Effect of wastewater-born bacteria on algal growth and nutrients removal in wastewater-based algae cultivation system," *Bioresource Technology*, 167, pp. 8-13, 2014.
- [8] I., Rawat, R. R., Kumar, T., Mutanda and F., Bux, "Dual role of microalgae: Phytoremediation of domestic wastewater and biomass production for sustainable biofuels production," *Applied Energy*, 88, pp. 3411-3424, 2011.
- [9] L. D., Zhu, E., Hiltunen, E., Antila, J. J., Zhong, Z. H., Yuan and Z. M., Wang, "Microalgae biofuels: Flexible bioenergies for sustainable development," *Renewable and Sustainable Energy Reviews*, 30, pp. 1035-1046, 2014.
- [10] W. Y., Cheah, T. C., Ling, P. L., Show, J. C., Juan, J.-S., Chang and D.-J., Lee, "Cultivation in wastewater for energy: A microalgae platform," *Applied Energy*, 179, pp. 609-625, 2016.
- [11] E., Jankowska, A. K., Sau and P., Oleskoicz-Popiel, "Biogas from microalgae: Review on microalgae's cultivation, harvesting and pretreatment for anaerobic digestion," *Renewable and Sustainable Energy Reviews*, 75, pp. 692-709, 2017.
- [12] M., Kroger and F., Muller-Langer, "Review on possible algal-biofuel production processes," *Biofuels*, 3(3), pp. 333-349, 2012.
- [13] I., Ozkurt, "Qualifying of safflower and algae for energy," *Energy Educ Sci Technol Part A*, 23, pp.145-151, 2009.
- [14] S., Schwede, A., Kowalczyk, M., Gerber and R., Span, "Influence of different cell disruption techniques on mono digestion of algal biomass," World Renew Energy Congress Linkoping. Sweden. 2011.
- [15] L., Moreno-Garcia, K., Adjalle, S., Barnabe and G. S. V., Raghavan, "Microalgae biomass production for a biorefinery system: Recent advances and the way towards sustainability," *Renewable and Sustainable Energy Reviews*, 76, pp. 493-506, 2017.
- [16] L., Brennan 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*, 14, pp. 557-577, 2010.
- [17] T. M., Mata, A. A., Martins and N. S., Caetano, "Microalgae for biodiesel production and

- other application: A review,” *Renewable and Sustainable Energy Reviews*, 14, pp. 217-232, 2010.
- [18] V., Patil, K. Q., Tran and H. R., Giselrod, “Toward sustainable production of biofuels from microalgae,” *Int J Mol Sci*, 9, pp. 1188-1195, 2008.
- [19] Y., Christi, “Biodiesel from microalgae,” *Biotech Adv*, 25, pp. 294-306, 2007.
- [20] J., Sheeahan, T., Dunahay, J., Benemann, and P., Roessler, “A look back at the US Depart of Energy's Aquatic Species Program-Biodiesel,” from *Algal*, 1998.
- [21] W., Zhou, P., Chen, M., Min, X., Ma, J., Wang, R., Griffith, F., Hussain, P., Peng, Q., Xie, Y., Li, J., Shi, J., Meng and R., Ruan, “Environment-enhancing algal biofuel production using wastewaters,” *Renewable and Sustainable Energy Reviews*, 36, pp. 256-269, 2014.
- [22] W. J., Oswald, H. B., Gotaas, C. G., Golueke and W. R., Kellen, “Algae in waste treatment,” *Sewage and Industrial Wastes*, 29, pp. 437-455, 1957.
- [23] K. V., Ajayan, M., Selvaraju, P., Unnikannan and P., Sruthi, “Phycoremediation of Tannery Wastewater Using Microalgae Scenedemus Species,” *Int J Phytoremeaist*, 17, pp. 907-916, 2015.
- [24] J.-Y., An, S.-J., Sim, J. S. Lee and B. W., Kim, “Hydrocarbon production from secondarily treated piggery wastewater by the green alga *Botryococcus braunii*,” *J Appl Phycol*, 15, pp. 185-191, 2003.
- [25] S., Sawayama, T., Minowa, Y., Dote and S., Yokoyama, “Growth of the hydrocarbon-rich microalgae *Botryococcus braunii* in secondarily treated sewage,” *Appl Microbio Biotechnol*. 38, 1992.
- [26] O., Mudimu, N., Rybalka, T., Bauersachs, J., Born, T., Friedl, and R., Schulz, “Biotechnological screening of microalgae and cyanobacteria strains for biogas production and antibacteria and antifungal effects,” *Metabolites*, 4, pp. 373-393, 2014.
- [27] Q. X., Kong, L., Li, B., Martinez, P., Chen and R., Ruan, “Culture of microalgae *Chlamydomonas reinhardtii* in wastewater for biomass feedstock production,” *Appl Biochem Biotechnol*, 160, pp. 9-18, 2010.
- [28] Y., Li, Y.-F., Chen, P., Chen, M., Min, W., Zhou, B., Martinez, J., Zhu and R., Ruan, “Characterization of a microalga *Chlorella* sp. well adapted to highly concentrated municipal wastewater for nutrient removal and biodiesel production,” *Bioresource Technology*, 102, pp. 5138-5144, 2011.
- [29] R., Chen, R., Li, L., Deitz, Y., Liu, R. J., Stevenson, and W., Liao, “Freshwater algal cultivation with animal waste for nutrient removal and biomass production,” *Biomass Bioenergy*, 39, pp. 128-138, 2012.
- [30] L., Wang, Y., Wang, P., Chen and R., Ruan, “Semi-continuous cultivation of *Chlorella vulgaris* for treating undigested and digested dairy manures,” *Appl Biochem Biotechnol*, 162, pp. 2324-2332, 2010.
- [31] I. T. D., Cabanelas, J., Ruiz, Z., Arbib, F. A., Chinalia, C., Garrido-Perez, F., Rogalla, I. A. Nascimento and J. A., Perales, “Comparing the use of different domestic wastewaters for coupling microalgal production and

- nutrient removal,” *Bioresource Technology*, 131, pp. 429-436, 2013.
- [32] S., Chinnasamy, A., Bhatnagar, R. W., Hunt and K. C., Das, “Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications,” *Bioresource Technology*, 101, pp. 3097-3105, 2010.
- [33] M., Sacristan de Alva, V. M., Luna-Pabello, E., Cadena and E., Ortiz, “Green microalgae *Scenedesmus acutus* grown on municipal wastewater to couple nutrient removal with lipid accumulation for biodiesel production,” *Bioresource Technology*, 146, pp. 744-748, 2013.
- [34] E., Suali and R., Sarbatly, “Conversion of microalgae to biofuel,” *Renewable and Sustainable Energy Reviews*, 16, pp. 4316-4342, 2012.
- [35] T. M., Mata, A. A., Martins and N. S. Caetano, “Microalgae for biodiesel production and other applications: a review,” *Renewable and Sustainable Energy Reviews*, 14, pp. 217-232, 2010.
- [36] M. A., Borowitzka, “In: Anderson, R.A. editor. Algal culturing technique,”. *New York: Elsevier, Academic Press*, pp. 205-218, 2005.
- [37] R., Putt M., Singh, S., Chinnasamy and K. C., Dasa, “An efficient system for carbonation of high-rate algae pond water to enhance CO<sub>2</sub> mass transfer,” *Bioresource Technology*, 102, pp. 3240-3245, 2011.
- [38] I., Rawat, R. R., Kumar, T., Mutanda and F., Bux, “Biodiesel from microalgae: A critical evaluation from laboratory to large scale production,” *Applied Energy*, 103, pp. 444-467, 2013.
- [39] A., Singh, P. S., Nigam and J. D., “Murphy, Mechanism and challenges in commercialisation of algal biofuels,” *Bioresource Technology*, 102, pp. 26-34, 2011.
- [40] C. U., Ugwu, H., Aoyagi and H., Uchiyama, “Photobioreactors for mass cultivation of algae,” *Bioresource Technology*, 99, pp. 4021-4028, 2008.
- [41] R., Davis, A. Aden and P. T., Pienkos, “Techno-economic analysis of autotrophic microalgae for fuel production,” *Applied Energy*, 88, pp. 3524-3531, 2011.
- [42] J., Milano, H. C., Ong, H. H., Masjuki, W. T., Chong, M. K., Lam, P. K., Loh and V., Vellayan, “Microalgae biofuels as an alternative to fossil fuel for power generation,” *Renewable and Sustainable Energy Reviews*, 58, pp. 180-197, 2016.
- [43] M. B., Tasic, L. F. R., Pinto, B. C., Klein, V. B. Veljkovic and R. M. Filho, “*Botryococcus braunii* for biodiesel production,” *Renewable and Sustainable Energy Reviews*, 64, pp. 260-270, 2016.
- [44] J. K., Pittman, A. P., Dean and O., Osundeko, “The potential of sustainable algal biofuel production using wastewater resources,” *Bioresource Technology*, 102(1), pp. 17-25, 2011.
- [45] N., Pragma, K. K., Pandey and P. K., Sahoo, “A review on harvesting, oil extraction and biofuels production technologies from microalgae,” *Renewable and Sustainable Energy Reviews*, 24, pp. 159-171, 2013.
- [46] Y., Nurdogan and W. J., Oswald, “Tube setting rate of high-rate pond algae,” *Water Science Technology*, 33, pp. 229-241, 1996.

- [47] L., Christenson and R., Sims, “Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts,” *Biotechnology Advances*, 29, pp. 686-702, 2011.
- [48] K., Tsukahara and S., Sawayama, “Liquid fuel production using microalgae,” *J Jpn Petrol Inst*, 48(5), pp. 251–259, 2005.
- [49] M., Satin, “Microalgae,” <<http://www.fao.org/ag/ags/Agsi/MICROALG.htm>> [accessed 20.11.17], 2017.
- [50] J., Clark and F., Deswarte, “Introduction to chemicals from biomass,” In: Stevens CV, editor. Wiley series in renewable resources. John Wiley & Sons. 2008.
- [51] S. A., Razzak, M. M., Hossain, R. A., Lucky, A. S., Bassi and H., de Lasa, “Integrated CO<sub>2</sub> capture, wastewater treatment and biofuel production by microalgae culturing-a review,” *Renewable and Sustainable Energy Reviews*, 27, pp. 622–653, 2013.
- [52] H. B., Goyal, D., Seal and R. C., Saxena, “Bio-fuels from thermochemical conversion of renewable resources: a review,” *Renewable and Sustainable Energy Reviews*, 12(2), pp. 504–517, 2008.
- [53] A. V., Bridgwater and G. V. C., Peacocke, “Fast pyrolysis processes for biomass,” *Renewable and Sustainable Energy Reviews*, 4, pp. 1–73, 2000.
- [54] V., Patil, K.-Q., Tran and H. R., Giselrad, “Towards sustainable production of biofuels from microalgae,” *International Journal of Molecular Sciences*, 9(7), pp.1188–1195, 2008.
- [55] P., McKendry, “Energy production from biomass (part 2): conversion technologies,” *Bioresource Technology*, 83(1), pp. 47–54, 2002.