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Potential of Algal Biodiesel Production in Jordan

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Abstract

The need for renewable and eco-friendly fuels arises from the adverse environmental impacts of the conventional fossil fuels. Microalgae cultivation has received considerable interest lately in the academic and industrial fields as a potential source for biofuels production as well as other byproducts such as pharmaceuticals, pigments, and animal feed. Despite their simple structures, microalgae are promising feedstock for the production of biofuels due to their high growth rate and lipid content compared to other energy crops. One of the major setbacks facing the large-scale production of microalgal biofuels is the relatively high production cost due to nutrient and energy input requirements. In this study, the feasibility of microalgae cultivation in Jordan for biodiesel production was investigated. The microalgae cultivation system was assumed to be an open raceway pond with a net area of 1 km^2 and a total algal broth volume of 250,000 m^3. Different cultivation scenarios were discussed and the materials and energy inputs were based on three literature studies. It was found that relying on the production of biodiesel alone is not economically feasible and will have a negative energy balance. However, by incorporating other processes such as the anaerobic digestion of the algal biomass as well as adapting different cultivation techniques that could reduce the cultivation energy, it is expected that the process will become feasible and will have a positive cash-flow.

Keywords: Jordan, microalgae, biodiesel, anaerobic digestion, biofuels

INTRODUCTION

Significant efforts have been geared towards finding renewable clean energy sources. As of now, most of the world's energy comes from fossil fuels such as oil, natural gas, and coal. This has adversely affected the environment due to Greenhouse gas (GHG) emissions (Abu Hajar et al., 2017b; Chen et al., 2011; Mata et al., 2010; Williams & Laurnes, 2010).

Biofuels are renewable fuels derived from energy crops such as sugar, starch, and microalgae. Microalgae biodiesel, which is produced via the transesterification of algal neutral lipids to form fatty acid alkyl ester, is a renewable alternative to the conventional diesel. The advantages of utilizing microalgae as a feedstock for the production of biodiesel include the high yield compared to other energy crops, eliminating the need for freshwater and fertile soil, the non-seasonality of algal growth, and the no competition with food production (Abu Hajar et al., 2017a; Abu Hajar et al., 2017b; Show et al., 2017).

Despite the previous advantages, the most significant disadvantage facing the algal biodiesel production is the high cultivation costs compared to conventional diesel. Hence, it is desirable to seek alternative cultivation, harvesting, and extraction techniques that will cut down the production costs (Abu Hajar et al., 2017b; Mata et al., 2010; Milledge, 2011). The literature is abundant with studies on the feasibility and lifecycle assessment of algal biodiesel, and most of those studies indicated that the process has a negative net energy balance; however, the process can become more feasible if other byproducts besides biodiesel are considered (Gnansounou & Raman, 2016). Furthermore, utilizing wastewater as a nutrient source and the cultivation of marine microalgae could significantly reduce the cultivation costs (Ishika et al., 2017).

In this study, the cultivation of microalgae for the production of biodiesel is investigated in Jordan. 96% of Jordan's energy need is imported; as there is no oil or gas production in the country. Hence, there is a strong incentive to utilize renewable energy sources such as solar and biomass especially that Jordan witnesses some of the strongest irradiance levels in the world for long periods in the year. In fact, one of the country's imminent goals is to generate 30% of its electricity using indigenous resources and reduce its oil and gas imports by the year 2020. Furthermore, relying entirely on imports is not secure due to the political turmoil in the neighboring countries. As a result, the country has supported initiatives and projects to produce renewable energy. In 2012, the Jordanian government has passed the Renewable Energy and Efficiency Law (REEL), which established direct proposal approach from the private sector for renewable projects and it required the National Electric Power Company (NEPCO) to purchase electricity from renewable sources while the connection to the grid is on NEPCO's expense, and all systems and equipment purchased for renewable energy projects are sales tax and customs duties exempt (Davies et al., 2016).

Currently, all microalgae cultivation studies in Jordan are lab-scale studies, and to the author's best knowledge, there are no industrial-scale facility for algal cultivation. Hence, the objectives of this study are to assess the feasibility of the industrial production of algal biodiesel in Jordan and to identify bottlenecks and potential improvements that will enhance the economics of algal biodiesel production.

MATERIALS AND METHODS

Site selection

Jordan has an excellent potential for renewable energy projects due to the high global radiation levels with more than 300 sunny days per year (Etier et al., 2010). Several locations in Jordan can be selected for the large-scale cultivation of microalgae, and for our study, five provinces were screened initially as shown in Figure 1 (blue markers). Light and temperature are the most important limiting factors in algal cultivation (Mata et al., 2010). Hence, it is desirable to select the location that will provide sufficient light and proper temperatures for algal cultivation. The historical records of temperature were used for comparison as shown in Figure 2.

Figure 1. Locations considered for microalgae cultivation in Jordan (map was generated using Google Maps)

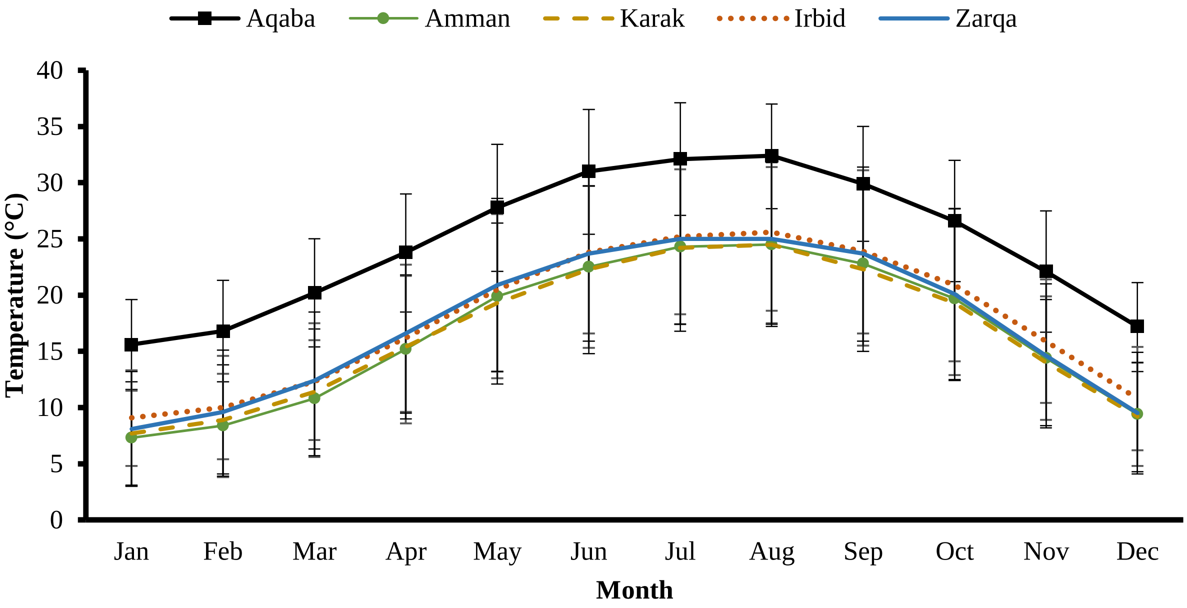

Figure 2. Average monthly temperatures in five Jordanian provinces (error bars represent the maximum and minimum average monthly temperatures). Source: climate-data.org

Clearly, the average monthly temperatures for Amman, Karak, Irbid, and Zarqa provinces have the same pattern with the highest temperatures recorded in July and August whereas the lowest temperatures are often recorded around January. However, temperatures in Aqaba (Jordan's southernmost point) are significantly higher than the other four provinces. The average annual monthly temperature in Aqaba is 24.6 °C and the range is 15.6 – 32.4 °C. Hence, it appears that Aqaba is the most attractive alternative for cultivating microalgae; as the ideal temperature for the growth of many algal species is 25 °C, even though the temperature can reach extremely high values (> 40 °C) during summer days. Furthermore, Aqaba is the only coastal city in Jordan, which provides an advantage of utilizing seawater for the cultivation of marine microalgae rather than utilizing freshwater in other provinces given that Jordan is one of the world's poorest countries in terms of freshwater resources. As a result, Aqaba province is proposed for the large-scale cultivation of microalgae in Jordan. The location of the microalgae cultivation facility is recommended in the vicinity of a power plant for the potential utilization of flue gas as a carbon source. Another attractive location would be near a wastewater treatment plant, where treated wastewater can be used as a nutrient source, besides, if the treatment plant utilizes biogas for its operations, the flue gas could potentially be utilized as a carbon source.

The average daily solar radiation incident on one square meter in Aqaba is 6,300 W.h/m^2/d (ca. 1,200 µmol/m^2/s) ranging from 3,791 W.h/m^2.d in January to 7,929 W.h/m^2.d in June (ca. 760 – 1500 µmol/m^2/s) (National Energy Research Center, 2010). Even though light is attenuated significantly through the culture depth, the high incident solar radiation levels might still be sufficient; as the photosynthesis saturation is at approximately 100 – 200 µmol/m^2/s (Chisti, 2016).

Cultivation system

Microalgae cultivation can be accomplished in open or closed bioreactors. Each system has its pros and cons; however, open cultivation systems such as outdoor raceway ponds are favored for the commercial production of algal biomass due to the lower construction and operating costs despite the higher potential of contamination (Abu Hajar et al., 2017a; de Godos et al., 2014; Mata et al., 2010). The most attractive open cultivation system is raceway ponds, which are constructed of concrete, plastic, or compacted earth material. The depth of algal cultures is typically 0.1 – 0.3 m to ensure sufficient light across the depth, and mixing is achieved via the use of a paddlewheel that is operated to achieve 0.1 – 0.3 m/s water surface velocities (Abu Hajar et al., 2017a; Chisti, 2016). For this study, it is assumed that the culture depth in the ponds is 0.25 m and that net area for cultivation is 1 km^2; hence, the total algal broth volume is 250,000 m^3. Practically, the cultivation area is divided among several ponds running in parallel, but for this study, one pond with the same equivalent area is assumed. As shown in Figure 3, the microalgae cultivation facility starts with a cultivation system such as open raceway ponds. The cultivation mode initially will be batch until reaching the peak concentration, that is when the cultivation mode switches to continuous by feeding the microalgae with fresh nutrient medium and withdrawing an equal volume of the algal broth. The dilution ratio (nutrient medium flow divided by the volume of the reactor) has to be less than the maximum specific growth rate in order to avoid biomass washout and this process is typically done during the daylight (Chisti, 2016).

The biomass is then harvested using one or a combination of different techniques such as centrifugation, flocculation/sedimentation, filtration, or dissolved air flotation. Lipid is then extracted using a solvent such as hexane, and biodiesel is produced via the transesterification of the lipid (Chisti, 2016; Gnansounou & Raman, 2016).

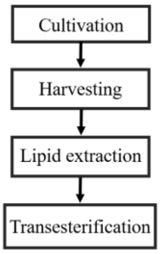

Figure 3. Algal biodiesel production stages

Microalgae selection

The use of saline water for the cultivation of microalgae is an attractive approach for the production of algal biodiesel in places with limited fresh water resources such as Jordan. However, evaporation has to be taken into consideration as this may result in elevated salinity levels. Saline microalgae have different levels of tolerance to salinity. The change in salinity imposes osmotic stress on the cell which can result in plasmolysis or cells bursting (Ishika et al., 2017). Several saline microalgae species have been studied and reported to yield high biomass and lipid productivities. For instance, the microalga *Dunaliella tertiolecta* has been reported to have a 0.12 g/L/d biomass productivity, 40% lipid content, and 20 – 60 mg/L/d lipid productivity (Chen et al., 2011; Ishika et al., 2017). *Dunalliella salina* is also an excellent candidate for the production of biodiesel as well as other byproducts. It has been indicated that its biomass productivity can reach 0.3 g/L/d with 35% lipid content. Furthermore, the cultivation of this species is advantageous due to its temperature and salinity tolerance (Ishika et al., 2017). *Nannochloropsis* sp. has received considerable interest; due to its biomass and lipid productivities (0.21 g/L/d and 61 mg/L/d, respectively) (Chen et al., 2011; Griffiths & Harrison, 2009; Rodolfi et al., 2009). Therefore, the cultivation of any of the above species seems as a reasonable selection for the large-scale production of algal biodiesel in Jordan.

Nutrients

The major nutrients needed for the algal growth include carbon, nitrogen, and phosphorus. Carbon is an important element for the growth of microalgae. Approximately, 1.83 kg of CO_2 is required to grow 1 kg of algal biomass. Hence, it is necessary to supply the algal culture with carbon dioxide; as atmospheric carbon dioxide is not sufficient. This is best achieved by installing a system of carbon dioxide injection coupled with pH signal. Hence, once the pH exceeds a certain level, carbon dioxide is injected to reduce the pH to the desired level (Chisti, 2016). Since providing pure carbon dioxide is not economically justified for producing algal biomass, a sustainable source of carbon dioxide could be the flue gas from fossil fuels burning (Chisti, 2016; de Godos et al., 2014; Gnansounou & Raman, 2016). For instance, de Godos et al. (2014) reported the successful cultivation of microalgae using diesel heating boiler flue gas which was composed of CO_2 (10.6%) and other gases such as CO, NO_x, and SO_2. The flue gas was cooled to air temperature and compressed to 2 bar before it was being supplied to the microalgae cultures. Some of the difficulties associated with utilizing flue gas as a carbon source for the cultivation of microalgae include the potential release of carbon dioxide on the ground level, the length of pipeline necessary for supplying this carbon source, and the need for NO_x and SO_x stripping (Chisti, 2016; de Godos et al., 2014; Gnansounou & Raman, 2016). The proposed location of the facility near a power plant or a wastewater treatment plant would make carbon dioxide supplement achievable at significantly lower costs compared to importing pure carbon dioxide from other sources.

Nitrogen and phosphorus are key elements to the growth of microalgae. Nitrogen can be supplied in the nitrate, ammonium, or organic forms whereas orthophosphate is the preferred form of phosphorus. For the sustainable cultivation of microalgae, it is recommended to utilize readily available nutrient sources such as wastewater or the anaerobic digestion effluent; which can reduce the cultivation operational costs significantly (Abu Hajar et al., 2017b; Choi & Lee, 2012). According to Beal et al. (2012a), the production of 1 kg of algal biomass requires 90 g of nitrogen and 10 g of phosphorus. Furthermore, the energy equivalents of nitrogen and phosphorus are 59 and 44 MJ/kg, respectively (Beal et al., 2012b). Hence, the overall energy associated with nitrogen and phosphorus is 5.75 MJ/kg algal biomass. Assuming that the lipid content in the algal biomass is 30% and the extraction efficiency is 80%, then the input energy associated with nitrogen and phosphorus is 24 MJ/kg biodiesel, which is approximately two thirds of the calorific value of biodiesel (37.8 MJ/kg). Hence, it is clear that in order to make biodiesel production feasible, it is necessary to rely on a readily available nutrient source such as wastewater or other organic liquid wastes.

Energy and Materials Input

The cultivation of microalgae requires the input of energy and chemicals at different stages of the process. For example, mixing, harvesting, extraction, and transesterification are all processes that require the input of energy. Solvents and flocculants are also needed for the successful production of algal biodiesel.

There are several lifecycle assessment and feasibility studies on the production of algal biodiesel. As a result, there is a huge variability in the costs associated with the production of 1 kg biodiesel in the literature. In this paper, three studies were selected as sources of energy and materials input data. The data obtained from the three sources are shown in Table 1 where the energy and materials requirements are presented for the production of 1 kg algal biomass as well as the production of 1 kg biodiesel. All of these studies assumed the cultivation of *Chlorella* sp., and the reported numbers in MJ equivalent per kg depend strongly on the cultivation conditions of each study, the lipid content as well as the extraction efficiency. A summary of the three studies is presented below.

Table 1 Energy and materials requirements for the production of 1 kg of algal biomass and 1 kg of algal biodiesel (MJ equivalent per kg)

	Beal et al. (2012b)		Lardon et al. (2009)		Gnansounou & Raman (2016)	
Parameter	kg biomass	kg biodiesel	kg biomass	kg biodiesel	kg biomass	kg biodiesel
Energy						
Cultivation	1.24	5.37	1.26	7.50	3.30	12.24
Harvesting	2.09	9.03	15.23	90.32	3.36	12.46
Extraction	0.24	1.04	1.45	8.60	0.71	2.62
Biodiesel synthesis	0.46	1.99	0.15	0.90	1.55	5.75
Nutrients						
Carbon dioxide	13.41	58.11	12.86	76.23	-	-
Nitrogen	5.31	23.00	2.72	16.11	0.92	3.41
Phosphorus	0.44	1.91	-	-	0.22	0.82
Other materials						
Flocculants	7.08	30.67	0.02	0.12	0.25	0.92
Solvents	0.83	3.60	0.88	5.24	1.38	5.11

Beal et al. (2012b) assumed a highly productive scenario based on experimental data with 80 mg/L/d biomass productivity and 30% lipid fraction. Cultivation was assumed to be in a closed outdoor bioreactor, and harvesting to be accomplished via advanced flocculation. Lardon et al. (2009) conducted a life-cycle assessment of algal biodiesel by the extrapolation of lab-scale data, industrial information, and Ecoinvent database data. The estimation was based on 100 ha open raceway pond culture that is 30 cm deep and the paddlewheel is operating at 0.25 m/s velocity with an algal concentration of 0.5 g/L and 20 – 30 g/m^2/d biomass productivity. They considered normal and low nitrogen conditions although it was assumed that no separate step for nitrogen starvation exists. Harvesting is accomplished via the use of flocculation and pH adjustment followed by thickening then dewatering. Extraction is accomplished by hexane extraction either on dried biomass or direct extraction from wet paste, where 90% solids content in the algal paste is desired to be consistent with data extrapolated from soybean oil extraction. They recommended the wet extraction method although it is not yet applicable on an industrial scale; hence, only data from the dry extraction were presented here. Gnansounou and Raman (2016) studied the feasibility of the cultivation of marine microalgae in seawater using stripped and cooled flue gas as a carbon source. The cultivation facility was assumed to be located in a coastal area in Southern India with a 100,000 t biodiesel/year capacity. Portion of the nutrients from downstream processes are assumed to be returned back to the algal cultivation system for recycling; hence, the lower nutrient requirements compared to the other two studies. Harvesting the biomass is assumed to be accomplished by a settling tank followed by dissolved air flotation unit, centrifugation, and finally dewatering. Extraction was assumed to be using a solvent (hexane) with a 91% extraction efficiency and biodiesel was produced via the transesterification of lipids. In their model, it was also assumed that the production of other byproducts such as succinic acid is also possible, while remaining biomass can be anaerobically digested and glycerol can be sold.

One of the major differences between the three studies was the harvesting energy. Lardon et al. (2009) estimated that 90.32 MJ is needed for harvesting to produce 1 kg biodiesel. The majority of that energy is heating energy whereas the other authors did not indicate the need for heating as a method for harvesting. Furthermore, as can be seen from Table 1, a significant portion of energy is required for providing nutrients (carbon dioxide, nitrogen, and phosphorus); however, nutrients requirements according to Gnansounou and Raman (2016) are minimized due to relying on sustainable production pathway utilizing flue gas and recycling nutrients from downstream processes. As a result, the data provided by Gnansounou and Raman (2016) will be used to assess the feasibility of the algal biodiesel production in Jordan; especially that they proposed cultivating marine microalgae in a coastal area, which is the same approach proposed in this study.

RESULTS AND DISCUSSION

As stated earlier, the proposed cultivation facility has a net cultivation area of 1 km^2 with a 0.25 m culture depth. Assuming a lipid productivity of 60 mg/L/d, and an 80% extraction efficiency, the overall biodiesel production from the facility will be 12,000 kg biodiesel per day. The input and output energy equivalents for the production of 1 kg biodiesel are presented in Figure 4.

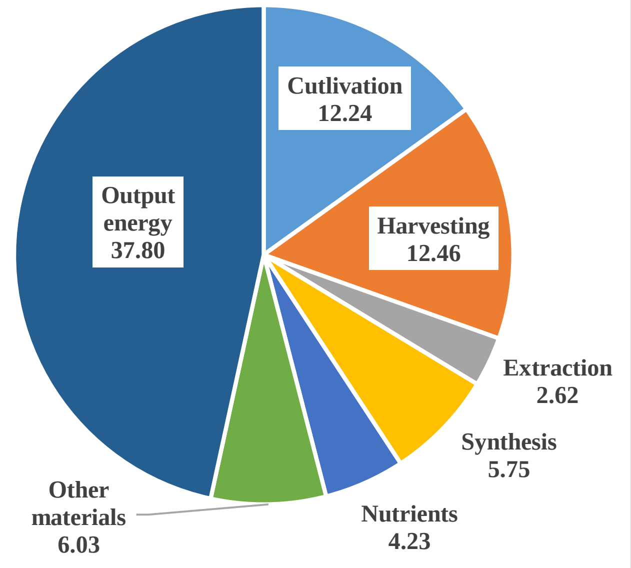

Figure 4 Input and output energy and material (MJ) for the production of 1 kg biodiesel

As shown in Figure 4, the production of 1 kg biodiesel has a negative energy balance; since the input energy required adds up to 43.33 MJ/kg biodiesel, whereas the heating value of 1 kg biodiesel is 37.8 MJ/kg. As mentioned earlier, this was based on the scenario provided by Gnansounou and Raman (2016). So for the proposed facility, it is estimated that there will be a net loss of 66,360 MJ energy equivalent per day. Assuming the price of 1 MJ is $0.28 (based on the conversion from kWh to MJ), the daily loss is approximately $1,800, which also does not include other operating and maintenance costs and overhead. Therefore, it is clear that algal biodiesel production through this approach is not viable unless the government provides a subsidy, which is an unrealistic approach to compensate the losses and only reach breakeven, as the Jordanian government faces many challenges and there are other priorities where funds can be directed. Hence, the exploration of other methods and approaches to cut down the cost of producing algal biodiesel is desirable.

As stated earlier, the input and output energy and materials per 1 kg biodiesel were obtained from three studies and the data from Gnansounou and Raman (2016) were applied to our study due to the resemblance in the proposed location and cultivation approach. However, looking back at Table 1, it is clear that the cultivation energy (12.24 MJ/kg biodiesel) is significantly higher than the other two studies (the average cultivation energy for the other two studies is 6.44 MJ/kg biodiesel). Hence, if the cultivation energy can be reduced to a value of 6.44 MJ/kg, the process will have a positive net energy (+0.27 MJ/kg biodiesel). Some of the methods that can be utilized to reduce the cultivation energy is to use a variable operating speed for the paddlewheel. Operating the ponds at the optimal speed is needed during the day in order to optimize the photosynthetic yield; however, ponds could be run at suboptimal speeds during the night. Furthermore, if a readily available nutrient source such as wastewater treatment effluent or the anaerobic digestion liquid waste is used, the energy equivalent to fertilizers will be reduced even further and could become negligible (assuming no pumping is required). This will add 4.23 MJ to the balance, making the process more feasible. Finally, the de-oiled algal biomass can be utilized to add to the energy balance. Approximately, 3.57 kg biomass residue will be produced for each 1 kg biodiesel (Gnansounou & Raman, 2016). Anaerobic digestion of the algal biomass is a potential approach for further production of energy from the de-oiled biomass. It is estimated that the anaerobic digestion could generate an additional net energy of 9.14 MJ per kg biodiesel produced. Besides, the anaerobic digestion process leaves behind a nutrient-rich medium that can be readily utilized for algal cultivation. The combination of microalgae cultivation and anaerobic digestion is a promising approach for the sustainable production of biofuels; due to the many interconnections between the two processes. The de-oiled algal biomass can be digested anaerobically to produce biogas. The flue gas from the combustion of biogas can be utilized as a carbon source for the growth of microalgae and the digestate can be used as a nutrient source for the algal growth. Furthermore, the microalgae culture can be potentially used for scrubbing the carbon dioxide from the biogas (Abu Hajar et al., 2016).

For the complete picture, the algal production potential has to be investigated holistically and an integration between this process and the anaerobic digestion has to be evaluated. However, to increase the feasibility of the process, the anaerobic digestion yield should be increased by considering other feedstocks for the co-digestion such as food waste and activated sludge.

CONCLUSIONS

In this study, the feasibility of algal biodiesel production in Jordan was investigated. Different cultivation and harvesting scenarios were considered based on literature and life-cycle assessment studies. It was found that the algal biodiesel production has a negative energy balance. However, the cultivation energy can be reduced by fully exploiting the algal biomass, operating the algal raceway ponds at lower speeds during the night hours, and coupling the algal cultivation process with other processes such as the anaerobic digestion. This is predicted to produce a positive energy balance and the algal biodiesel production can then become profitable.

REFERENCES

[1] Abu Hajar, H. A., Riefler, R. G., & Stuart, B. J. 2017a. Cultivation of Scenedesmus dimorphus using anaerobic digestate as a nutrient medium. Bioproc Biosyst Eng. 40(8): 1197-1207.

[2] Abu Hajar, H. A., Riefler, R. G., & Stuart, B. J. 2017b. Cultivation of the microalga Neochloris oleoabundans for biofuels production and other industrial applications (a review). Appl Biochem Microbiol. 53(6): 640-653.

[3] Abu Hajar, H. A., Riefler, R. G., & Stuart, B. J. 2016. Anaerobic digestate as a nutrient medium for the growth of the green microalga Neochloris oleoabundans. Environ Eng Res. 21(3): 265-275.

[4] Beal, C. M., Stillwell, A. S., King, C. W., Cohen, S. M., Berberoglu, H., Bhattarai, R. P., ... & Hebner, R. E. 2012a. Energy return on investment for algal biofuel production coupled with wastewater treatment. Water Environ Res. 84(9): 692-710.

[5] Beal, C. M., Hebner, R. E., Webber, M. E., Ruoff, R. S., Seibert, A. F., & King, C. W. 2012b. Comprehensive evaluation of algal biofuel production: experimental and target results. Energies. 5(6): 1943-1981.

[6] Chen, C. Y., Yeh, K. L., Aisyah, R., Lee, D. J., & Chang, J. S. 2011. Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: a critical review. Bioresour Technol. 102(1): 71-81.

[7] Chisti, Y. 2016. Large-scale production of algal biomass: raceway ponds. In Algae Biotechnology (pp. 21-40). Springer International Publishing.

[8] Choi, H. J., & Lee, S. M. 2012. Effects of microalgae on the removal of nutrients from wastewater: Various concentrations of Chlorella vulgaris. Environ Eng Res. 17(S1): S3–S8.

[9] Davies, M., Hodge, B., Schellekens, G., & Ahmad, S. 2016. Developing Renewable Energy Projects: A Guide to Achieving Success in the Middle East, 3rd Edition.

[10] de Godos, I., Mendoza, J. L., Acién, F. G., Molina, E., Banks, C. J., Heaven, S., & Rogalla, F. 2014. Evaluation of carbon dioxide mass transfer in raceway reactors for microalgae culture using flue gases. Bioresour Technol. 153: 307-314.

[11] Etier, I., Al Tarabsheh, A., & Ababne, M. 2010. Analysis of solar radiation in Jordan. Jordan J Mech Ind Eng. 4(6): 733-737.

[12] Gnansounou, E., & Raman, J. K. 2016. Life cycle assessment of algae biodiesel and its co-products. Appl Energ. 161: 300-308.

[13] Griffiths, M. J., & Harrison, S. T. 2009. Lipid productivity as a key characteristic for choosing algal species for biodiesel production. J Appl Phycol. 21(5): 493-507.

[14] Ishika, T., Moheimani, N. R., & Bahri, P. A. 2017. Sustainable saline microalgae co-cultivation for biofuel production: A critical review. Renew Sust Energ Rev. 78: 356-368.

[15] Lardon, L., Helias, A., Sialve, B., Steyer, J. P., & Bernard, O. 2009. Life-cycle assessment of biodiesel production from microalgae. Environ Sci Technol, 43(117): 6475-6481.

[16] Mata, T. M., Martins, A. A., & Caetano, N. S. 2010. Microalgae for biodiesel production and other

applications: a review. Renew Sust Energ Rev. 14(1): 217-232.

[17] Milledge, J. J. 2011. Commercial application of microalgae other than as biofuels: a brief review. Rev Environ Sci Biotechnol. 10(1): 31-41.

[18] National Energy Research Center. 2010. Jordan Solar Irradiance and Ambient Temperature Bulletin for the year. Retrieved from www.cp.org.jo

[19] Rodolfi, L., Chini Zittelli, G., Bassi, N., Padovani, G., Biondi, N., Bonini, G., & Tredici, M. R. 2009. Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low- cost photobioreactor. Biotechnol Bioeng. 102(1): 100-112.

[20] Show, P. L., Tang, M. S., Nagarajan, D., Ling, T. C., Ooi, C. W., & Chang, J. S. 2017. A Holistic Approach to Managing Microalgae for Biofuel Applications. Int J Mol Sci. 18(1): 215.

[21] Williams, P. J. L. B., & Laurens, L. M. 2010. Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economyics. Energ Environ Sci. 3(5): 554-590.