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Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance

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ABSTRACT

This research examines the life-cycle water and nutrients usage of microalgae-based biodiesel production. The influence of water types, operation with and without recycling, algal species, geographic distributions are analyzed. The results confirm the competitiveness of microalgae-based biofuels and highlight the necessity of recycling harvested water and using sea/wastewater as water source. To generate 1 kg biodiesel, 3726 kg water, 0.33 kg nitrogen, and 0.71 kg phosphate are required if freshwater used without recycling. Recycling harvest water reduces the water and nutrients usage by 84% and 55%. Using sea/wastewater decreases 90% water requirement and eliminates the need of all the nutrients except phosphate. The variation in microalgae species and geographic distribution are analyzed to reflect microalgae biofuel development in the US. The impacts of current federal and state renewable energy programs are also discussed to suggest suitable microalgae biofuel implementation pathways and identify potential bottlenecks.

1. Introduction

Renewable energy plays a critical role in addressing issues of energy security and climate change at global and national scales. In the US, the federal government passed the energy independence and security act (EISA) in 2007 which requires a gradual increase in the production of renewable fuels to reach 36 billion gallons per year by 2022. Furthermore, 28 states have passed their own mandatory renewable energy legislation (EIA, 2009). For example, Arizona and California will replace 15% and 20% of their electricity sales with renewable energy by 2020, respectively. Texas has a mandate for 5880 MW of renewable electricity capacity by 2015. Other states have mandates to reduce greenhouse gas (GHG) emissions. For instance, Minnesota's strategic goal is to reduce GHG emissions by 80% between 2005 and 2050 (Olabisi et al., 2009).

First-generation liquid biofuels, such as corn-based ethanol in the US and sugarcane ethanol in Brazil (Sims et al., 2010), have already been widely produced. However, the mass production of first-generation liquid biofuels has resulted in a series of problems related to food prices, land usage, and carbon emissions (Sims et al., 2010). Thus, EISA limits the production of corn-based ethanol and increases the production of advanced biofuels (GAO, 2009). Microalgae-based biofuels are an appealing choice (Zhang et al., 2010) to meet these mandates because of microalgae's (1) rapid growth rate [cell doubling time of 1–10 days (Schenk et al., 2008)], (2) high lipid content [more than 50% by cell dry weight (Hu et al., 2008)], (3) smaller land usage [15–300 times more oil production than conventional crops on a per-area basis (Li et al., 2010)], and (4) high carbon dioxide (CO_2) absorption and uptake rate (Jorquera et al., 2010). Given these advantages, microalgae-based biofuels have been recognized as the "third-generation of biomass energy" (Gressel, 2008) and the "only current renewable source of oil that could meet the global demand for transport fuels" (Schenk et al., 2008).

To date, microalgae-based biofuel production has not yet been commercialized to large-scale. Debates exist regarding life-cycle impacts of large-scale microalgae-based biofuel production, especially the impact on water usage. In particular, what is the water consumption per acre of land used for algal feedstock production? In addition, what are the availability and feasibility of water that can be used for algal feedstock production in the United States? For instance, large-scale microalgae biodiesel production has been criticized for the significant amount of freshwater usage (DOE, 2009). However, microalgae-based biodiesel production may consume much less potable water than conventional feedstock-based biodiesel production if microalgae are grown in sea water or wastewater (Groom et al., 2008). Yet, to our knowledge, no study has investigated the life-cycle water usage, or water footprint, of microalgae biodiesel production using different water sources

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(i.e., using freshwater, seawater, or wastewater) while water footprints for biofuel production using conventional feedstocks has been reported (Chiu et al., 2009; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009).

This study quantitatively examines the water footprint of biodiesel production using microalgae as the feedstock. The processes studied in this research include cultivation in an open pond, harvesting, drying, extraction, and esterification. The functional unit is defined as the production of 1 kg of microalgae-based biodiesel. Several production options are examined including using freshwater, seawater, or wastewater for algal culture and with or without recycling harvested water. Policy implications of large-scale production in the US are discussed.

2. Methods

2.1. Microalgae-based biodiesel production system

The life-cycle of the microalgae biodiesel production system includes the processes of culture, harvest, drying, extraction, and esterification. First, together with added nutrients, culture water (freshwater, seawater or wastewater) (Wang et al., 2008), is fed to open pond. During the culture process, freshwater is added regularly to compensate water loss and avoid salt buildup due to evaporation. In other words, a certain amount of freshwater has to be consumed in the production of microalgae biodiesel no matter what type of culture water is used. Microalgae are harvested when the biomass and lipid content reached certain levels. After harvest, the culture water can be partially recycled by pumping it back into the culture pond. The remaining water is discharged directly into wastewater treatment system. Algae are then dried. Finally, lipid is extracted from the concentrated (wet or dry) microalgae and esterified to produce biodiesel.

The microalgae biodiesel production system is characterized by the particular algae species' growth rate and lipid content which vary widely. In this study, *Chlorella vulgaris* is used as a representative species to study the water footprint of microalgae biodiesel production. Other common species are examined as well to measure the impact of species-specific characteristics on water footprint.

2.2. Data

2.2.1. Culture

During the culture process, water is lost primarily owing to evaporation (Chiu et al., 2009; DOE, 2009). In this study, lake evaporation rate is used to approximate the evaporation rate in open ponds based on methods reported by Farnsworth and Thompson (1982). In addition, temperature and solar radiation data which affects microalgal growth rate and lipid accumulation (Clarens et al., 2010) were obtained from the national solar radiation database (NSRDB). Microalgal lipid content is cited from the research of Hu et al. (2008) and Chisti (2008). The addition of nutrients is calculated based on their concentration in ponds (Li and Hu 2005).

2.2.2. Harvesting and drying

Harvesting, the process of collecting algal cells from dilute suspension culture, is characterized by the solid content and recovery rate. Solid content is the mass ratio of microalgae to water after harvesting, whereas the recovery rate refers to the ratio of the harvested microalgae mass to the microalgae mass after culture. Sim et al. (1988) provide the values for the two parameters.

Similarly, drying is a further dewatering process that is also characterized by solid content and recovery rate. In general, the solid content after harvest can easily exceed 90%, while the recovery rate can reach 95% (DOE, 2009).

2.2.3. Extraction and esterification

The extraction and esterification process for microalgae biodiesel production is similar to that of producing soybean biodiesel when the slurry content is greater than 90% (Lardon et al., 2009). Thus, this study applies the average water usage in extraction and esterification of soybean biodiesel production to approximate that of producing microalgae biodiesel, i.e., 2–10 l of water usage per liter of biodiesel produced (Dominguez-Faus et al., 2009). Note that not all the harvested microalgae can be converted into biodiesel. In particular, the yield for *C. vulgaris* extraction is approximately 70% (Lee et al., 2010). Chemical methanolysis using an alkali catalysis process (Ban et al., 2002) is then used for esterification with a yield that can exceed 96% (Antolin et al., 2002).

3. Results

A case of culturing *C. vulgaris* in an open pond under the conditions similar to the summer in California is studied to examine the water footprint and life-cycle nutrients consumption of microalgae-based biodiesel production. The growth rate, lipid content and growth cycle of *C. vulgaris* are obtained from Demirba (2009), Li et al. (2008), and Chisti (2007).

3.1. Water usage

Fig. 1a shows the water usage of microalgae biodiesel production at different life-cycle stages. Without recycling harvested water, the water footprint is approximately 3726 kg-water/kg-biodiesel. About 84.1% of the water is discharged after harvest, while the rest is lost by either pond evaporation or drying. The water footprint can be reduced to as low as 591 kg-water/kg-biodiesel if all the harvest water is recycled. The water usage of culture, drying, extraction or esterification does not vary with the change of the harvest water recycling rate. In other words, no matter how much harvest water is recycled, the water footprint caused by other processes, mostly culture and drying, is generally unavoidable.

In addition to freshwater, seawater, and wastewater can also be utilized for algal culture. In particular, wastewater refers to secondary effluents characterized with low biochemical oxygen demand (BOD) and chemical oxygen demand (COD) but high inorganic nitrogen and phosphorous. Fig. 1b shows the water footprint when using freshwater, seawater or wastewater at different recycling rates of harvested water. The results indicate that using seawater or wastewater can reduce the life-cycle freshwater usage by as much as 90%. However, a significant amount of freshwater must be used for culture no matter whether sea/wastewater serves as the culture medium or how much harvested water is recycled.

3.2. Nutrient usage

Fig. 1c shows the usage of key inorganic nutrients in the Life-cycle of microalgae biodiesel production with and without harvest water recycling. Not surprisingly, harvested water recycling can significantly reduce the nutrient usage. In particular, the life-cycle usages of nitrogen, phosphorous, potassium, magnesium, and sulfur are 0.33, 0.71, 0.58, 0.27, and 0.15 kg/kg-biodiesel without harvest water recycling. However, when the harvest water is 100% recycled, the usage of these nutrients decreases by approximately 55%.

Fig. 1d illustrates the usage of nutrients using different culture media while the harvest water is 100% recycled. Using sea/wastewater for algal culture can reduce nitrogen usage by 94% and eliminate the need of potassium, magnesium, and sulfur. Overall,

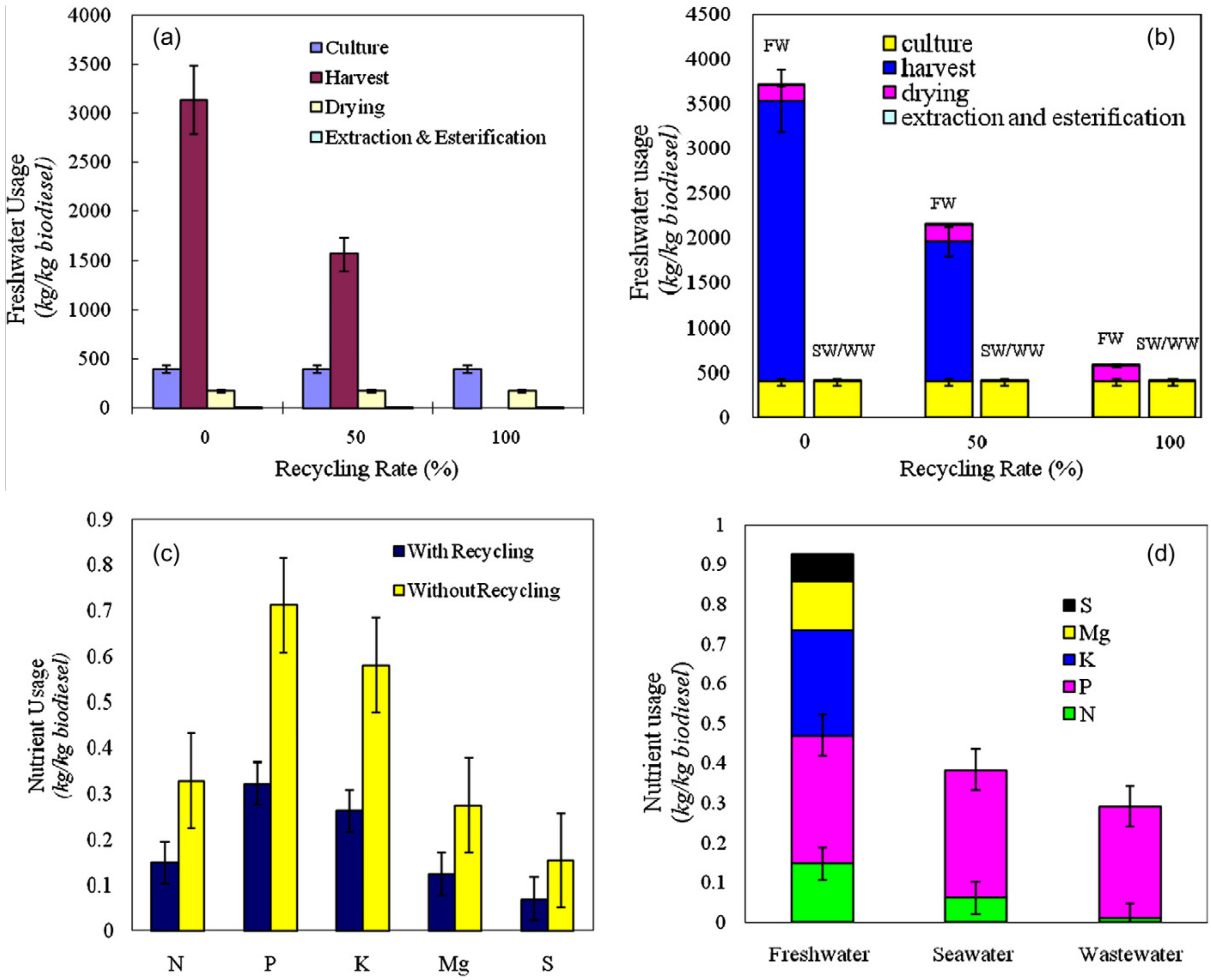

Fig. 1. For producing 1 kg biodiesel from microalgae, (a) water footprint using freshwater (FW) medium; (b) water footprint using seawater (SW) or wastewater (WW) as the culture medium; (c) life-cycle usage of nutrients in FW medium with/without harvest water recycling; and (d) life-cycle usage of nutrients in SW or WW medium with 100% harvest water recycling.

nutrient usage increases as the recycling rate of harvested water decreases.

3.3. Sensitivity analysis

Sensitivity analysis is conducted to understand how parameter variations affect the results and to identify parameters that are critical for quantifying the water footprint of microalgae biodiesel production. Parameters analyzed in this study include evaporation rate, algal growth rate, algal lipid content, slurry content after harvesting, recovery rate after harvesting and slurry content after drying. As shown in Fig. 2a, evaporation rate, algal growth rate, algal lipid content, and slurry content after harvest are the most sensitive parameters. Furthermore, by combining the variations of these parameters from literature, it can be found that growth rate is the most sensitive factor (Fig. 2b).

There are also uncertainties from the sources of data, mostly the literature cited in this research. Given that some of these studies do not report uncertainties associated with their data sources in detail, it is difficult to comprehensively quantify this type of uncertainties in this research. However, using existing information from the literature, we found the differences between life-cycle stages are more significant than the deviations caused by uncertainties from data sources, as shown in Fig. 1. While a careful examination may be necessary in the future for other purposes, for this research a detailed analysis of uncertainties associated with data sources is less important.

3.4. Comparison with other feedstocks

In general, water footprint of biofuel production is considered as three categories including green, blue and gray water footprint (Gerbens-Leenes et al., 2009). Green and blue water footprints refer to the evaporation during production process. Gray water footprint refers to the water finally emitted as wastewater. In this study, the water footprint associated with the culture process is caused by evaporation, thus considered as the green and blue water footprints.

Table 1 compares the water footprint of microalgae biodiesel production in this study with results for other feedstocks. It is

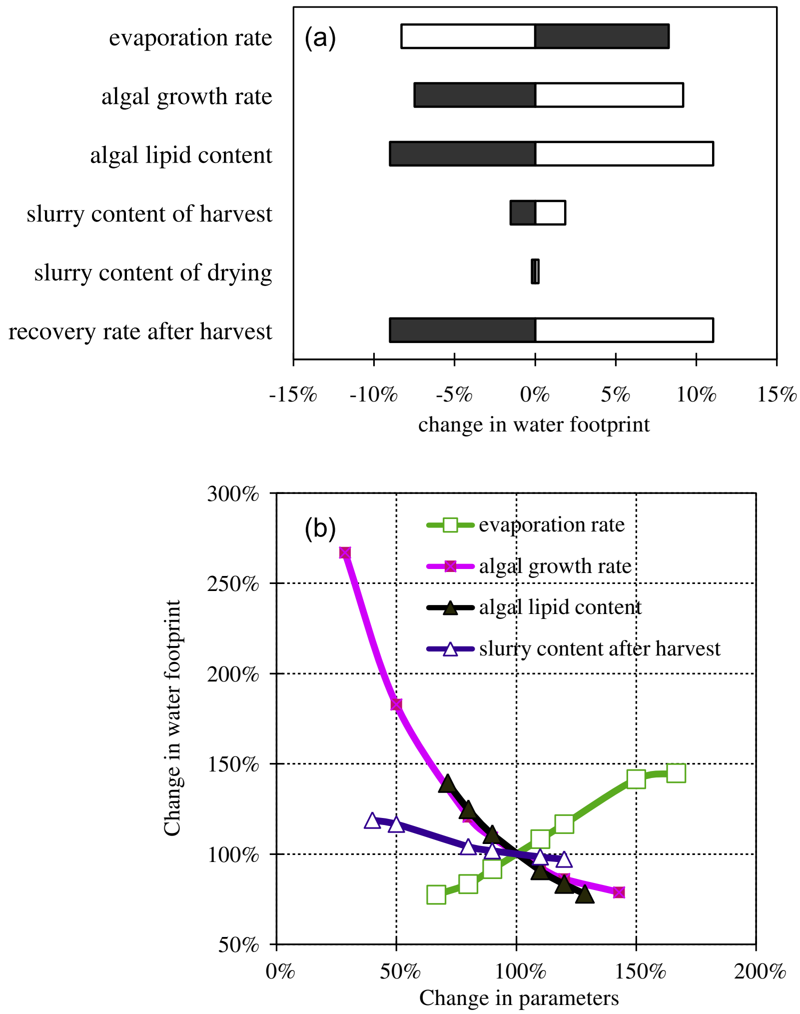

Fig. 2. (a) Water footprint of *C. vulgaris*-based biodiesel production relative to different parameter variations. The centerline represents the baseline case. The black and white shaded values indicate positive and negative relationships, respectively; (b) sensitivity analysis of parameters. Each curve indicates the change in water footprint associated with the variation of a parameter while all other parameters are kept the same as in the *C. vulgaris* case. Data for evaporation rate are taken from Farnsworth and Thompson (1982), data for algal growth rate and lipid content are taken from (Hu et al., 2008; Demirba, 2009; Chisti, 2008), and data for the slurry content after harvest come from Sim et al. (1988).

Table 1
Comparison of microalgae biodiesel's water footprint with other feedstocks.

	Blue and green water footprint (kg-water/kg-biodiesel)	Total water footprint (kg-water/kg-biodiesel)
Maize[a]	1583–1972	4015
Potatoes[a]	1214–1684	3748
Sugar cane[a]	1978–2131	3931
Sugar beet[a]	1268–1284	2168
Sorghum[a]	3153–6647	15,331
Soybean[a]	6539–7521	13,676
Switchgrass [a]	2189	NA
Corn[b]	263–956	NA
Microalgae[c]	280–400	NA
Microalgae[d]	399	591–3650

[a] Dominguez-Faus et al. (2009) and Gerbens-Leenes et al. (2009). All feedstocks except soybean are used to produced ethanol rather than biodiesel. These values present energy-equivalent of biodiesel in kg.
[b] Dominguez-Faus et al. (2009), Chiu et al. (2009), and Clarens et al. (2010).
[c] DOE (2009) and Chinnasamy et al. (2010).
[d] The results are from this study, using freshwater as the culture medium. The variation of total water footprint is caused by the variation of recycle rate.

obvious that microalgae biodiesel is very competitive as compared to other conventional feedstocks in terms of both blue/green water footprint and total water footprint.

4. Discussion

4.1. Microalgae species variation

Algal growth rate and lipid content, the two most important parameters of microalgae, both have negative impacts on the water footprint of microalgae biodiesel production. That is, increasing growth rate and lipid content can reduce the water footprint, as shown in Fig. 3. However, growth rate and lipid content conflict with each other given that lipid accumulation is likely to occur with nutrient depletion which happens when the growth rate slows (Goldberg and Cohen, 2006). Thus a trade-off must be made between growth rate and lipid content when choosing the suitable microalgae species for producing biodiesel.

In this study, water footprints of eleven other microalgae strains were also studied and the results were compared with *C. vulgaris*. Their growth rates are reported by Sheehan et al. (1998), while their lipid contents are provided by Chisti (2007). It is found that the water footprint using other microalgae species is generally 1–6 times higher than that using *C. vulgaris*. In particular, the water footprints of *Chaetoceros gracilis*, *Cyclotella cryptic*, and *Nannochloropsis* sp. are comparable with that of *C. vulgaris*.

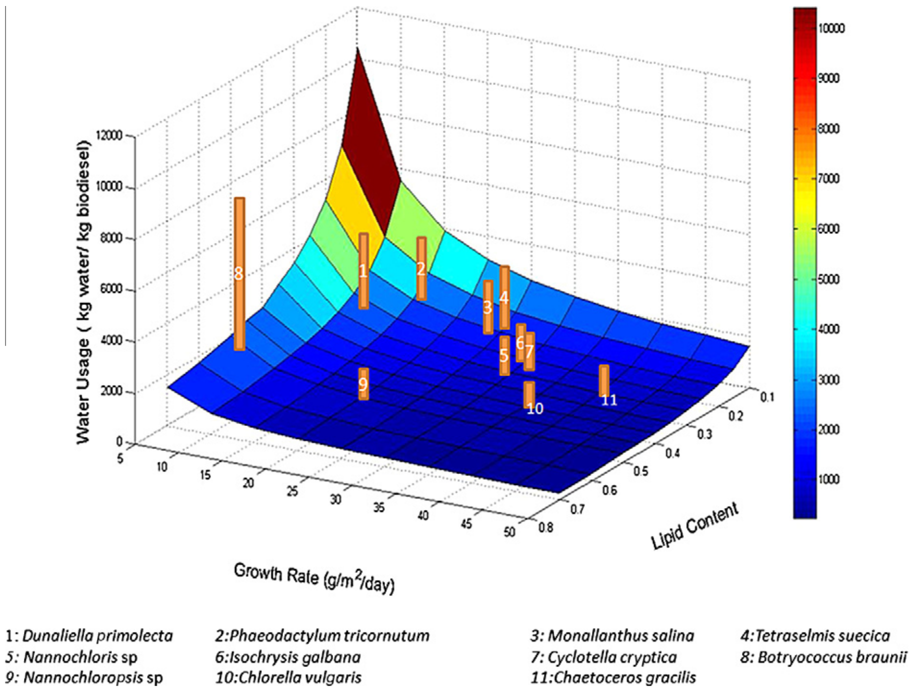

Fig. 3. Water footprint of *C. vulgaris*-based biodiesel production under different algal growth rates and lipid contents. Each bar refers to one reported microalgae species. Details can be found in the electronic annex Table S6.

4.2. Spatial variation

Solar radiation, temperature, and evaporation, varying geographically, are critical for microalgae growth. In general, microalgae grow faster with high solar radiation and temperature, which can lower the water footprint. However, evaporation rate will increase drastically when radiation and temperature increases, which in turn increase the water footprint (Fig. 4). Thus, there is another trade-off to be taken into account when choosing where to grow microalgae.

Based on Fig. 4, the water footprint of biodiesel production in different US states can be predicated using each state's annual average solar radiation temperature, and evaporation data (electronic annex Figure S4). Overall, the water footprint of microalgae-based biodiesel production gradually decreases from north to south as solar radiation and temperature increase. Roughly, a boundary can be drawn across the US, from the northern border of California to the northern border of New York, based on the geographic variation of water footprint in microalgae biodiesel production. Approximately, the water footprint in states north of the boundary is more than 1500 kg-water/kg-biodiesel, whereas the states south of the boundary have smaller water footprints. In addition, the water footprint of microalgae biodiesel production generally decreases from west to east, as the evaporation rate in the east is lower than that in the west at the same latitude. Florida and Hawaii are the most suitable states for microalgae-based biodiesel production, and Arizona has the third smallest water footprint among all states.

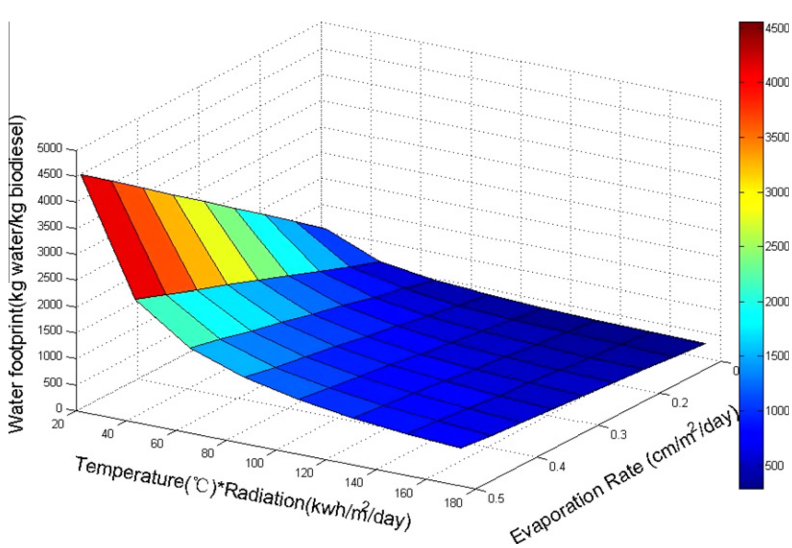

Fig. 4. Water footprint (kg-water/kg-biodiesel) of *C. vulgaris*-based biodiesel production under different climatic conditions.

Table 2
Water footprint and life-cycle nitrogen and phosphate usage of using *C. vulgaris*-based biodiesel to achieve the EISA goal of one billion gallons of biodiesel production in 2022.

Harvest water recycled	Freshwater		Seawater		Wastewater	
	Yes	No	Yes	No	Yes	No
Freshwater usage (billion gallons/year)	1238	10920	181	181	181	181
As a percentage of national usage[a] (%)	9.7	85.7	1.4	1.4	1.4	1.4
Nitrogen (10^6 kg)	564	2188	230	886	359	1380
As a percentage of national usage[b] (%)	4.3	16.6	1.7	6.7	2.7	10.5
Nitrogen cost (million $)	754	2925	308	1185	480	1845
As a percentage of biodiesel price (%)	8	31	3.3	12.5	5.1	19.5
Phosphate (10^6 kg)	1211	4731	1048	4094	1211	4731
As a percentage of national usage[b] (%)	26.5	103.5	22.9	89.6	26.5	103.5
Phosphate cost (million $)	2153	8412	1865	7279	2153	8412
As a percentage of biodiesel price (%)	22.7	88.8	19.7	76.8	22.7	88.8

[a] National water usage statistics are from Kenny et al. (2009).
[b] National nitrogen and phosphate usage and cost statistics are from USDA (2010).

4.3. Policy implications

At the national level, EISA has mandated the production of renewable fuels by 2022. In particular, EISA has limited the annual production of the currently widely used corn-based ethanol to no more than 15 billion gallons. The production of advanced biofuels will gradually increase to reach 21 billion gallons, including one billion gallons of biomass-based diesel, by 2022. Based on the US annual average temperature, radiation, and evaporation rate, Table 2 lists the water footprint and life-cycle nitrogen and phosphate usage to achieve this biomass-based diesel goal by producing *C. vulgaris*-based biodiesel. This will increase the national usage of freshwater, nitrogen, and phosphate by 9.7%, 8%, and 22.7%, respectively, if harvested water is recycled and much more if harvest water is not recycled, using freshwater as the culture medium. Given that the United States has already faced water shortages to some extent, harvest water recycling can significantly reduce the footprint of freshwater, as shown in Table 2. Moreover, the world's supply of phosphate is in great danger of depletion (DOE, 2009), which must be taken into account when implementing microalgae biodiesel production at a large-scale. Possible solutions include screening microalgae for those able to live in a low-phosphate environment and using phosphate-rich water as the culture medium.

To date, there are 28 states which have established their own mandatory renewable energy goals (EIA, 2009). Table 3 lists some of these goals and their associated water footprints using *C. vulgaris*-based biodiesel to achieve according on each state's average temperature, radiation, and evaporation rate. In Arizona, California, and Ohio this plan seems easier, as the water footprint required is less than 10% of the current water usage in each of these states. In New York and Texas, meeting state mandates becomes more difficult if using freshwater as the culture medium. However, using sea/wastewater as the culture medium instead can significantly reduce the water footprints. In Rhode Island, microalgae biodiesel is obviously not a solution given its disproportionally high water footprint.

4.4. Technology Implications

Overall, using seawater or wastewater as the culture medium can reduce the water footprint of microalgae biodiesel production by approximately 35%. However, other considerations must be taken into account in future research, such as life-cycle energy consumption including transportation and facility land use in large-scale production.

Table 3
Water footprint of *C. vulgaris*-based biodiesel production to meet the mandatory renewable energy goals in selected states.

State	Goal	Water footprint (billion tons)		Water footprint (as percentage of current usage)	
	Culture medium	Freshwater	Sea/wastewater	Freshwater (%)	Sea/wastewater (%)
AZ	15% electricity	0.7	0.3	8.5	3.0
CA	20% electricity	1.8	0.6	4.0	1.4
NY	24% electricity	2.3	0.8	16.5	5.8
OH	25% electricity	0.6	0.2	3.7	1.3
RI	16% total energy	0.5	0.2	2517	881
TX	5880 MW	1.9	0.7	33.9	11.9

Fortunately, alternative technologies are being developed to reduce the water footprint of microalgae biodiesel production, such as enclosed photobioreactor. Compared with an open pond, an enclosed photobioreactor can easily (1) generate a high density of microalgae per volume of water, (2) enable better control of the culture conditions, and (3) reduce water usage owing to lower evaporation. However, the enclosed photobioreactor system will significantly increase the cost of facility construction, operation and maintenance. Future investigation is required to fully understand the trade-offs of choosing between open ponds and enclosed photobioreactors.

5. Conclusions

This study quantifies the water footprint and nutrients usages during microalgae biodiesel production. 3726 kg water, 0.33 kg nitrogen, and 0.71 kg phosphate are required to generate 1 kg microalgae biodiesel if freshwater is used without recycling. Recycling harvest water reduces the water and nutrients usage by 84% and 55%, respectively. Using sea/wastewater as culture medium decreases 90% water requirement, and eliminates the need of all the nutrients except phosphate. Geographic and species variation are discussed to identify the potential species and locations for microalgae biodiesel production. Aimed at current renewable energy programs, the implementation pathways and the potential bottlenecks are suggested.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2010.07.017.

References

Antolin, G., Tinaut, F.V., Briceno, Y., Castano, V., Perez, C., Ramirez, A.I., 2002. Optimisation of biodiesel production by sunflower oil transesterification. Bioresour. Technol. 83, 111–114.

Ban, K., Hama, S., Nishizuka, K., Kaieda, M., Matsumoto, T., Kondo, A., Noda, H., Fukuda, H., 2002. Repeated use of whole-cell biocatalysts immobilized within

biomass support particles for biodiesel fuel production. J. Mol. Catal. B. Enzym. 17, 157–165.
Chinnasamy, S., Bhatnagar, A., Hunt, R.W., Das, K.C., 2010. Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications. Bioresour. Technol. 101, 3097–3105.
Chisti, Y., 2008. Biodiesel from microalgae beats bioethanol. Trends Biotechnol. 26, 126–131.
Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol Adv. 25, 294–306.
Chiu, Y.W., Walseth, B., Suh, S., 2009. Water embodied in bioethanol in the United States. Environ. Sci. Technol. 43, 2688–2692.
Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental life-cycle comparison of algae to other bioenergy feedstocks. Environ. Sci. Technol. 44, 1813–1819.
Demirba, A., 2009. Production of biodiesel from algae oils. Energy Sources 31, 163–168.
Department of Energy (DOE), National algal biofuels technology roadmap, 2009.
Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: A drink or drive issue? Environ. Sci. Technol. 43, 3005–3010.
Energy Information Administration (EIA), 2009. State renewable energy requirements and goals: update through, 2008.
Farnsworth, R.K., Thompson, E.S., 1982. Mean monthly, seasonal, and annual pan evaporation for the United States. NOAA technical Report NWS 34. US Department of Commerce.
Gerbens-Leenes, P.W., Hoekstra, A.Y., van der Meer, T.H., 2009. The water footprint of bioenergy. PNAS 106, 10219–10223.
Goldberg, I.K., Cohen, Z., 2006. The effect of phosphate starvation on the lipid and fatty acid composition of the fresh water eustigmatophyte Monodus subterraneus. Phytochemistry 67, 696–701.
Government Accountability Office (GAO), 2009. Biofuels potential effects and chanllenges of required increases in production and use. GAO-09-446.
Gressel, J., 2008. Transgenics are imperative for biofuel crops. Plant Sci. 174, 246–263.
Groom, M.J., Gray, E., Townsend, P.A., 2008. Biofuels and biodiversity: Principles for creating better policies for biofuel production. Conserv. Biol. 22, 1–8.
Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M., Darzins, A., 2008. Microalgal triacylglycerols as feedstocks for biofuel production: Perspectives and advances. Plant J. 54, 621–639.
Jorquera, O., Kiperstok, A., Sales, E.A., Embirucu, M., Ghirardi, M.L., 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresour. Technol. 101, 1406–1413.
Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009. Estimated use of water in the United States in 2005: US Geological Survey Circular 1344, 52.
Lardon, L., Helias, A., Sialve, B., Steyer, J.P., Bernard, O., 2009. Life-cycle assessment of biodiesel production from microalgae. Environ. Sci. Technol. 43, 6475–6481.
Lee, J., Yoo, C., Jun, S.Y., Ahn, C.Y., Oh, H.M., 2010. Comparison of several methods for effective lipid extraction from microalgae. Bioresour. Technol. 101, S75–S77.
Li, Q., Du, W., Liu, D.H., 2008. Perspective of microbioal oils for biodiesel production. Appl. Microbiol. Biotechnol. 80, 749–756.
Li, F.M., Hu, H.Y., 2005. Isolation and characterization of a novel antialgalal lelochemical from Phragmites communis. Appl. Environ. Microbiol. 71, 6545–6553.
Li, X., Hu, H.Y., Gan, K., Sun, Y.X., 2010. Effects of different nitrogen and phosphorus concentrations on the growth, nutrient uptake, and lipid accumulation of a freshwater microalga *Scenedesmus* sp. Bioresour. Technol. 101, 5494–5500.
Olabisi, L.S., Reich, P.B., Johnson, K.A., Kapuscinski, A.R., Suh, S., Wilson, E.J., 2009. Reducing greenhouse gas emissions for climate stabilization: Framing regional options. Environ. Sci. Technol. 43, 1696–1703.
Schenk, P.M., Thomas-Hall, S.R., Stephens, E., Marx, U.C., Mussgnug, J.H., Posten, C., Kruse, O., Hankamer, B., 2008. Second generation biofuels: High-efficiency microalgae for biodiesel production. Bioenerg. Res. 1, 20–43.
Sheehan, J.; Dunahay, T., Benemann J., Roessler P., 1998. A look back at the US Department of Energy's Aquatic Species Program-Biodiesel from Algae. National Renweable Energy Laboratory, www.nrel.gov/docs/fy04osti/34796.pdf.
Sim, T.S., Goh, A., Becker, E.W., 1988. Comparison of centrifugation, dissolved air flotation and drum filtration techniques for garvesting sewage-grown algae. Biomass 16 (1), 51–62.
Sims, R.E.H., Mabee, W., Saddler, J.N., Taylor, M., 2010. An overview of second generation biofuel technologies. Bioresour. Technol. 101, 1570–1580.
United States Department of Agriculture (USDA), 2010. US fertilizer use and price. http://www.ers.usda.gov/Data/FertilizerUse.
Wang, B., Li, Y., Wu, N., Lan, C.Q., 2008. CO_2 bio-mitigation using microalgae. Appl. Microbiol. Biot. 79, 707–718.
Zhang, X.Z., Hu, Q., Sommerfeld, M., Puruhito, E., Chen, Y.S., 2010. Harvesting algal biomass for biofuels using ultrafiltration membranes. Bioresour. Technol. 101, 5279–5304.