

Research Article

Theoretical calculations on the feasibility of microalgal biofuels: Utilization of marine resources could help realizing the potential of microalgae

Hanwool Park, Choul-Gyun Lee

National Marine Bioenergy R&D Center & Department of Biological Engineering, Inha University, Incheon, Republic of Korea

Microalgae have long been considered as one of most promising feedstocks with better characteristics for biofuels production over conventional energy crops. There have been a wide range of estimations on the feasibility of microalgal biofuels based on various productivity assumptions and data from different scales. The theoretical maximum algal biofuel productivity, however, can be calculated by the amount of solar irradiance and photosynthetic efficiency (PE), assuming other conditions are within the optimal range. Using the actual surface solar irradiance data around the world and PE of algal culture systems, maximum algal biomass and biofuel productivities were calculated, and feasibility of algal biofuels was assessed with the estimation. The results revealed that biofuel production would not easily meet the economic break-even point and may not be sustainable at a large-scale with the current algal biotechnology. Substantial reductions in the production cost, improvements in lipid productivity, recycling of resources, and utilization of non-conventional resources will be necessary for feasible mass production of algal biofuel. Among the emerging technologies, cultivation of microalgae in the ocean shows great potentials to meet the resource requirements and economic feasibility in algal biofuel production by utilizing various marine resources.

Received	10 APR 2016
Revised	23 OCT 2016
Accepted	25 OCT 2016
Accepted article online	26 OCT 2016

Supporting information
available online



Keywords: Biofuel map · Global estimation · Nutrients · Offshore cultivation · Photosynthetic efficiency

1 Introduction

Various renewable energy sources have been harnessed for energy production, but many of these produce electricity, which cannot be efficiently stored. Moreover, the volumetric and gravimetric energy density of the most-advanced batteries are much lower than those of liquid fuels [1]. Biofuels have long been considered potent, renewable alternatives to petroleum-based fuels because

they are carbon neutral and can be utilized by existing infrastructure and internal combustion engines with little or no modifications [1, 2].

Microalgae have recently received a great deal of attention because of their superior characteristics as feedstocks for biofuel production. Specifically, they have high photosynthetic efficiency (PE), ability to accumulate energy storage biochemicals, broad range of growth conditions, can be harvested frequently (e.g. every two weeks), do not require arable land, and are not major food sources [3–10]. Despite the excellent characteristics of microalgae as feedstock for biofuels, there are still many obstacles to large-scale commercial production of microalgal biofuel. Although a wide range of prices for algal biofuel have been reported (from 1.3–2.4 USD L⁻¹ [11–14] to 20 USD L⁻¹ [13]), it is clear that algal biofuel is not cost competitive with petroleum-based fuels or other biofuels, yet.

Many studies have estimated the maximum productivity of algal biofuels since microalgae have gained

Correspondence: Prof. Choul-Gyun Lee, Department of Biological Engineering, 100 Inha-Ro, Incheon 22212, Republic of Korea
E-mail: leecg@inha.ac.kr

Abbreviations: AP, aqueous phase; CAPEX, capital expenditure, GHGs, greenhouse gases; HTL, hydrothermal liquefaction; OPEX, operating expenditure, ORP, open raceway pond; PAR, photosynthetically active radiation; PBR, photobioreactor; PE, photosynthetic efficiency; TOE, ton of oil equivalent (1 TOE is equivalent to 41.9 GJ)

attention. Microalgal biofuel productivity ranges from 5.6 TOE ha⁻¹ y⁻¹ to 106.8 TOE ha⁻¹ y⁻¹ [4, 9, 13, 15–21]. In some cases, the data from lab-scale experiments are used to estimate the productivity of large-scale production, and arbitrary values for biomass productivity and lipid content are assumed in some cases. Moreover, the diversity of microalgae contributes to the highly variable estimations of algal biofuel productivity [4, 6, 9, 15, 16]. In most photoautotrophic algal cultures, the amount of light energy provided is one of the major factors determining microalgal biomass productivity. Some algal cultures use artificial lights for constant illumination or supplying light during the night to enable higher productivity [22]. Use of artificial lighting may be feasible for production of highly-valued compounds, such as pharmaceuticals and antioxidants. However, LEDs, which are one of the most energy-efficient lights, have up to 48% wall plug efficiency [23], while the theoretical maximum value of PE is 25.9% of photosynthetically active radiation (PAR) [24]. Therefore, consuming electricity to cultivate microalgae for biofuels has a very low energy conversion efficiency and is economically infeasible [25]. Consequently, sunlight should be used as the only energy source for algal cultures for biofuel production. In such cases, the maximum productivity of algal biofuels is ultimately limited by the amount of solar irradiance and PE of the culture system.

Several reports estimated microalgal biofuel productivity using solar irradiance information [9, 19, 26], but they only analyzed a few locations or considered only land area when determining biofuel potentials. Land-based open raceway ponds (ORPs) and closed photobioreactors (PBRs) have been the major technologies employed for algal cultivation, but development of water-based algal culture systems has been reported recently, claiming various advantages over conventional land-based systems [27–35]. Thus, it would be worth including the vast ocean area in analysis of maximum microalgal biofuel productivity.

In this study, the maximum microalgal biofuel productivity was calculated based on surface solar radiation, limits for capital and operation costs for economic feasibility of algal biofuel production were determined, and sustainability of global scale microalgal biofuel production was assessed. Various methods to improve economic feasibility and sustainability were then discussed.

2 Methods

2.1 Surface solar irradiation

Solar irradiance may be expressed as a function of latitude as described by Weyer et al. [26]. Top-of-atmosphere insolation shows a strong correlation with latitude, but various meteorological phenomena lead to significant deviations

in surface solar irradiance (Supporting information, Fig. S1 using supplementary data). For example, it is easy to assume that the latitude with the highest solar irradiance is 0°; however, it is actually 15° north because of the presence of an equatorial low pressure belt, which has high cloud covers and rainfalls. Therefore, calculation of maximum productivity should be based on the actual insolation data that to include the effects of climate conditions. For this study, the average annual surface solar irradiance data from 1983 to 2005 were obtained from the NASA Langley Research Center, Atmospheric Science Data Center, Surface Meteorological and Solar Energy (SSE) web portal supported by the NASA LaRC POWER Project (<https://eosweb.larc.nasa.gov/>). By using the insolation data recorded on the surface, climate and general weather conditions are considered in estimation of the biofuel potentials.

2.2 Calculation of maximum microalgal biofuel productivity

Calculation of maximum microalgal biofuel productivity was based on PE for two culture systems: land-based ORPs and flat-panel PBRs, and two different lipid contents of microalgae: lipid-moderate and lipid-rich, to investigate the effects of such differences in economic feasibility and sustainability of algal biofuel. PE values of ORPs and flat-panel PBRs were selected for calculation of maximum productivity as representatives of low-cost, horizontal culture systems with relatively lower PE and high-cost, vertical culture systems with relatively higher PE [36]. Cellular respiration, photosaturation, photoinhibition, mutual shading, etc., make it difficult to achieve the theoretical maximum in practical settings; thus, PE values achieved in actual culture systems are substantially lower than the maximum value of 25.9% PAR. In ORPs and flat-panel PBRs, 3.3% PAR and 11.1% PAR could be achieved [36]. The values used for the calculations are given in Table 1. Many factors, such as CO₂ supply, temperature, medium composition, pH, salinity, agitation, and dissolved oxygen (DO), affect algal growth and biomass productivity [3, 7, 16, 20, 27, 28, 37]. These factors are assumed to be within the optimal growth conditions for calculation of the highest biomass productivity that can be achieved in outdoor algal cultures with the sunlight as energy source.

Microalgae have the ability to alter their biomass composition in response to environmental conditions [5, 6, 38, 39]. In rare cases, lipid content can be increased up to 80% w/w [38], but in outdoor autotrophic culture conditions, lipid content in algal biomass is often below 30% [40–42]. Nevertheless, lipid productivity varies greatly by the strain of microalgae [5, 16, 38, 40, 42]. In this study, two lipid contents, 25 and 50%, and energy contents in the algal biomass, 20 MJ · kg⁻¹ and 30 MJ · kg⁻¹, were assumed for base case and high lipid content case, respectively [38,

Table 1. Major input values for calculations

	Case 1 (ORP-B)	Case 2 (ORP-H)	Case 3 (PBR-B)	Case 4 (PBR-H)	Reference
Annual solar irradiance ($\text{GJ} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$)		19 800–91 700			
PAR (% of total solar energy)			48.7		[24]
PE (% of PAR)		3.1		10.3	[36]
Biomass energy content ($\text{GJ} \cdot \text{t}^{-1}$)	20	30	20	30	[38, 43]
Average areal max. biomass productivity ($\text{t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$)	39	26	130	86	This study
Lipid content (%)	25	50	25	50	[38, 43]
Biofuel energy content ($\text{TOE} \cdot \text{t}^{-1}$)			0.86		
Average areal max. biofuel productivity ($\text{TOE} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$)	8.4	11	28	37	This study
Density of algal biofuel ($\text{t} \cdot \text{m}^{-3}$)			864		[5]
Water consumption ($\text{m}^3 \cdot \text{TOE}^{-1}$)		291		51	[59]
C content of biomass (%)			51.2		[37, 57, 63]
N content of biomass (%)			6.7		[37, 57, 63]
P content of biomass (%)			1.5		[37, 57, 63]
K content of biomass (%)			0.9		[37, 57, 63]

43]. The maximum microalgal biomass and biofuel productivities were calculated using the following equations:

$$\text{Max. Biomass Productivity} = \frac{(\text{Annual Solar Irradiance}) \times (\text{PAR}) \times (\text{PE})}{(\text{Biomass Energy Content})} \quad (1)$$

$$\text{Max. Biofuel Productivity} = (\text{Max. Biomass Productivity}) \times (\text{Lipid Content}) \times (\text{Biofuel Energy Content}) \quad (2)$$

The maximum biomass and biofuel productivities were calculated using Eq. (1) and (2) in the unit of $\text{t ha}^{-1} \text{y}^{-1}$ and $\text{TOE ha}^{-1} \text{y}^{-1}$, respectively, introducing the values in Table 1. A global map of maximum theoretically possible biofuel productivity (Fig. 1) based on the case 1 was created using the obtained SSE data for all latitudes and longitudes using SigmaPlot® software. The detailed calculation can be found in the Supporting information.

2.3 Economic feasibility of algal biofuels

High price is one of the major hurdles to commercialization of microalgal biofuels [3–6, 8, 12, 17, 21]. For economically feasible production of microalgal biofuels, the production cost should be comparable to that of other commercialized biofuels, ethanol and biodiesel from corn, sugarcane, oil palm, and soybean oil. The production costs for biofuels from conventional energy crops ranged from 0.21 to 0.99 USD L^{-1} [44–47]. In the case of biofuel production from microalgae, 1 USD L^{-1} was set as the cost to achieve economic feasibility. Many studies have analyzed the individual contributors such as land purchase, land construction, culture system construction, nutrients supply, water supply, power consumption, labor, tax, and interest debt to estimate the production cost of algal biofuel [6, 8, 12, 13]. Instead of analyzing individual factors, they were divided into two large sums: capital expenditure (CAPEX) and operating expenditure (OPEX). Limits

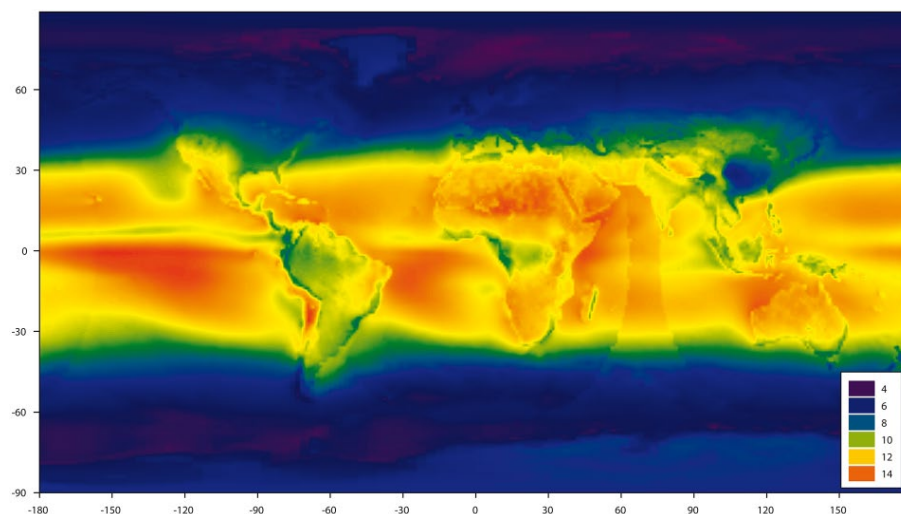


Figure 1. Maximum microalgal biofuel productivity around the globe based on the case 1 ($\ln \text{TOE ha}^{-1} \text{y}^{-1}$).

for CAPEX and OPEX to produce algal biofuel at 1 USD L⁻¹ were assessed based on the productivities from four cases using the following equation:

$$\text{Target Price of Biofuels} = \frac{\left(\frac{\text{CAPEX}}{\text{ROI}}\right) + (\text{OPEX})}{(\text{Max. Biofuel Productivity})} \quad (3)$$

2.4 Sustainability of algal biofuels

Suggested advantages of biofuel production from microalgae include high areal productivity, cultivation in marginal land, and ability to grow with relatively simple nutrients [3–5, 9, 15]. However, enormous quantities of resources, such as area, freshwater, and nutrients (carbon, nitrogen, phosphorus, and potassium) will be required in large-scale algal fuel production to replace a significant portion of a country's transportation fuel consumption. Sustainability of algal biofuel production at a global scale was assessed by comparing the requirements for resources with the current usage using the input parameters listed in Table 1. The potential for using marine resources to meet the requirements for resources was then analyzed.

3 Results and discussion

3.1 Maximum microalgal biofuel productivity based on surface solar irradiance

The maximum biofuel productivity ranged from 3.2 TOE ha⁻¹ y⁻¹ to 14.8 TOE ha⁻¹ y⁻¹ with an average of 8.4 TOE ha⁻¹ y⁻¹ for case 1 (Table 1). The corresponding maximum biomass productivities were 14.9–68.8 t ha⁻¹ y⁻¹ with 38.9 t ha⁻¹ y⁻¹ as the global average (Table 1). The

world maximum biofuel productivity map indicates that regions at lower latitude generally have higher maximum biofuel productivity, (Fig. 1). The tendency is more apparent when in the results based on the four cases are plotted against the latitude (Fig. 2). However, as mentioned above, the equatorial region did not have the highest biofuel productivity because of the Intertropical Convergence Zone, in which the weather is frequently cloudy and rainy all over the year. Nevertheless, the tropical zone had the highest overall biofuel productivity because of the substantially higher solar irradiance in the region (Fig. 2). Similar effects of climate conditions on the productivity were found at the sub polar zones, near 70°; however, unlike the tropical zone, biofuel productivity was lower in these areas than in the neighboring locations.

The productivities for case 2, 3, and 4 were 133, 333, and 444% of those of case 1, respectively (Table 1). The lipid content increased from 25% (cases 1 and 3) to 50% (cases 2 and 4), resulting in a 33% increase in maximum biofuel productivity (compare cases 1 vs. 2 and 3 vs. 4) and higher PE values in cases 3 and 4 led to 3.3-fold higher productivity compared to the lower PE values in cases 1 and 2 (Table 1). Table 1 also shows that the improvement in the productivity in response to the enhanced PE and lipid content (344%) was comparable to that observed in response to the maximum difference by location (362%). These results indicate that algal biofuel productivity can be substantially enhanced by improving algal culture technology for higher PE and lipid content.

The maximum algal biofuel productivities from each case were compared with the values from the literature (Fig. 3). The estimations and results of other studies were within the range of predictions from this study, except for one case. An exceptionally high algal biofuel yield prediction of up to 106 TOE ha⁻¹ y⁻¹ was reported by Chisti [10]. A very high lipid content, 70%, was assumed, which is

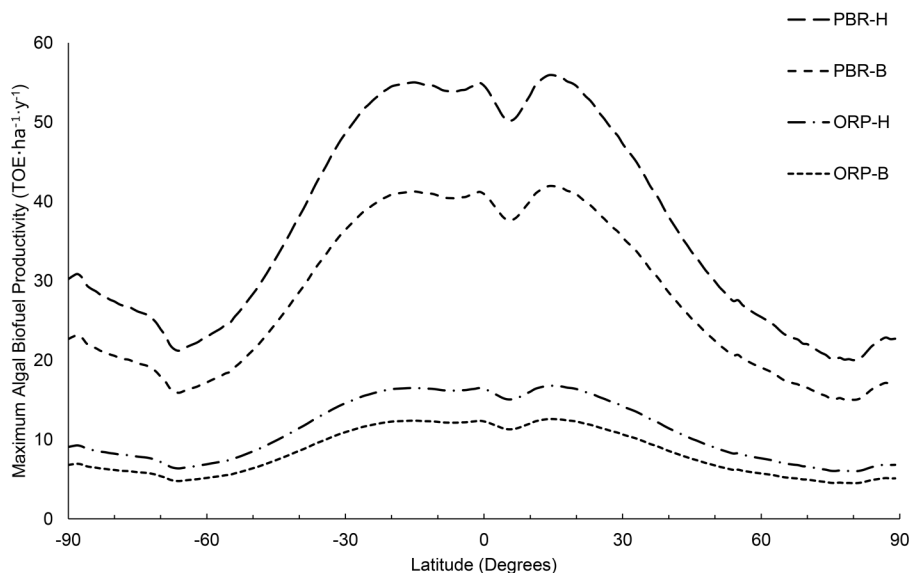


Figure 2. Maximum microalgal biofuel productivities by latitude based on 22-year average of surface solar irradiance.

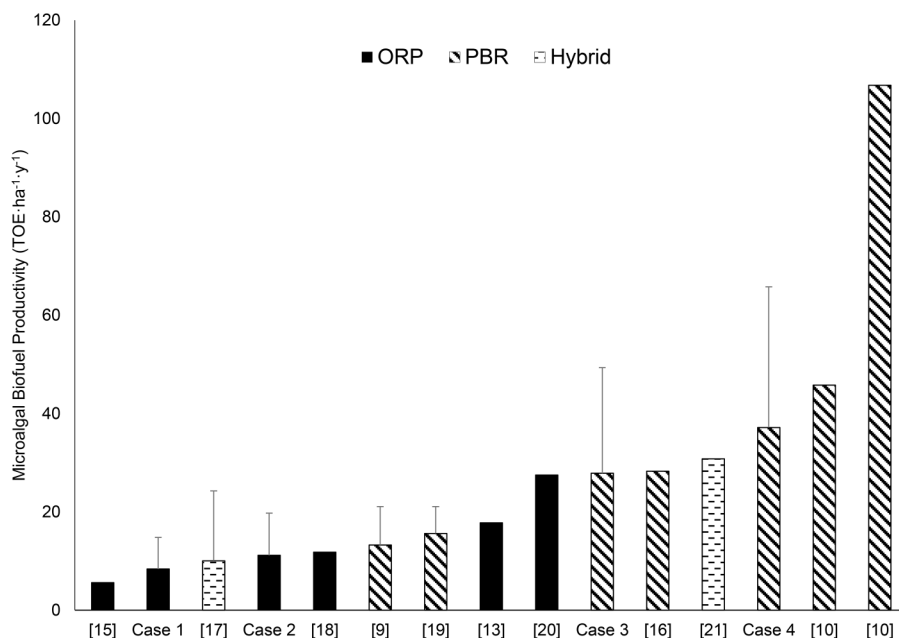


Figure 3. Comparison of microalgal biofuel productivities. The bars indicate maximum values if both average and maximum values were available.

difficult to achieve in outdoor cultivation [40–42], and temporal and spatial conditions were not taken into account in the estimation. Case 4 is based on the maximum PE and lipid content, reflecting the upper limit of algal biofuel productivity using sunlight. Therefore, the high productivities suggested would be difficult to achieve without breakthroughs in genetic modifications to enhance the PE of microalgae or PBR engineering. Indeed, the data from actual outdoor cultivation by Rodolfi et al. and Feng et al. were close to the estimations from case 3 [16, 20], showing that the current maximum productivity has not yet been achieved.

The global map of maximum algal biofuel productivities for case 1 also shows variations by longitude (Fig. 1). For example, the west coast of the North Americas has higher maximum algal biofuel productivity than the east coast because of climate differences. Interestingly, a large area of China shows lower biofuel potentials than the adjacent locations, appearing as a blue island. Many Chinese metropolitan cities suffer from extensive atmospheric pollution, which considerably reduces the amount of solar radiation reaching the surface [48].

Although the highest biofuel productivity was obtained from the mountains of Chile, the Pacific, Atlantic, and Indian Oceans offer very large areas with high maximum biofuel productivities (Fig. 1). Cultivation of microalgae in such regions using water-based algal culture systems could be an attractive alternative to land-based culture systems. Particularly, for countries without large areas of land with high solar radiation (e.g. Korea and the United Kingdom), deploying algal cultures in their exclusive economic zone (EEZ) or creating a joint offshore algae farm in international waters with high solar irradi-

ance would be an attractive option for algal biofuel production. While other regions can be affected by tropical storms such as typhoons, hurricanes, and cyclones, the Southeast Pacific Ocean and South Atlantic Ocean are free from such storms and would serve as great locations for microalgal biofuel production.

3.2 Economic feasibility of microalgal biofuels by culture systems and productivity

The limits for CAPEX and OPEX were estimated based on the global average maximum algal biofuel productivities using Eq. (3) (Fig. 4). The periods for return of investment (ROI) were assumed to be five or 20 years. As the total production cost cap was determined by the set price of biofuel and productivity, CAPEX and OPEX were inversely correlated to each other, refer to Eq. (3). While increases in productivity elevated the limits for both CAPEX and OPEX, ROI period only affected CAPEX. These results indicate that CAPEX and OPEX must be below one million USD ha⁻¹ and 50 000 USD ha⁻¹ y⁻¹, respectively, to achieve an algal biofuel price of 1 USD L⁻¹ under the maximum productivity scenario (case 4) (Fig. 4B). For ORPs, approximately 300 000 USD ha⁻¹ and 15 000 USD ha⁻¹ y⁻¹ were the maximum CAPEX and OPEX, respectively (Fig. 4B).

Three predicted values of capital and operation costs for ORP and a hybrid of ORPs and PBRs are plotted in Fig. 4 [12, 17, 21]. For a 400-ha algal biofuel plant using an open raceway pond, CAPEX and OPEX were estimated to be at least 250 000 USD ha⁻¹ and 20 000 USD ha⁻¹ y⁻¹ (square in Fig. 4) [12]. For a hybrid system, CAPEX and OPEX were predicted to be 272 482 USD ha⁻¹ and

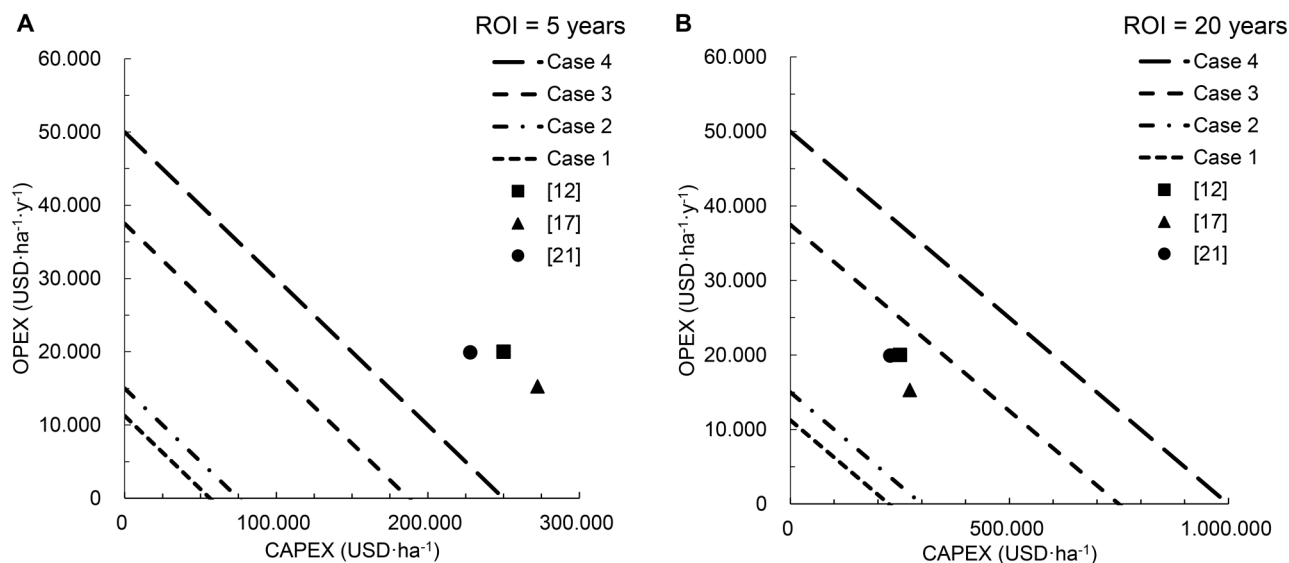


Figure 4. CAPEX and OPEX limits to produce algal biofuel at 1 USD L⁻¹ based on microalgal biofuel productivity. **A:** ROI = 5 years, **B:** ROI = 20 years.

15 270 USD ha⁻¹ y⁻¹ (triangle in Fig. 4) [17], while for another hybrid system they were 228 000 USD ha⁻¹ and 19 900 USD ha⁻¹ y⁻¹ (circle in Fig. 4), respectively [21]. With a five-year ROI, none of the culture systems were economically feasible (Fig. 4A), but when the ROI was increased to 20 years, they could be profitable with adequate algal biofuel productivity, roughly 23 TOE ha⁻¹ y⁻¹ (Fig. 4B). Moreover, the capital cost of PBRs was estimated to be substantially greater, at 940 000 USD ha⁻¹ [17]. Another study also reported 906 255 USD ha⁻¹ as the capital cost for PBRs [14]. In such cases, an exceptionally high productivity (case 4) and low annual cost would be required to generate profit by producing only biofuel, but the estimated OPEX for PBRs was 216 232 USD ha⁻¹ y⁻¹ [14], which was beyond the limit for operation cost of 50 000 USD ha⁻¹ y⁻¹, even with the productivity of case 4. Without generating extra revenue by selling other products, the facility will not reach the break-even point. In contrast to the estimated values, an actual facility of Cyanotech in Hawaii required about 460 000 USD ha⁻¹ for site preparation for of the raceway pond alone [49]. The characteristics of the site for Cyanotech's facility, which was covered by volcanic rocks, added an extra 34 398 USD ha⁻¹ for land clearing; nevertheless, it is still notable how expensive land construction for an algal culture systems can be.

As the results indicate, substantial reductions in CAPEX and OPEX while maintaining or improving biofuel productivity are needed to deliver economic feasibility. The algal culture systems account for 53% to 83% of the capital cost [8, 12, 21], and as seen in the case of Cyanotech, the cost for land construction also has a significant impact on the CAPEX. Thus, low-cost algal culture systems that do not require extensive construction would be needed. Labor, electricity, and nutrient supply

are generally the major contributors to OPEX [3, 6, 8, 12]. In particular, decreasing the cost for nutrient supply can contribute to considerable reductions (>50%) in total cost in algal biomass and biofuel production [3, 6]. Therefore, recovering and reusing nutrients in algal biomass or utilizing non-fertilizer nutrients would be essential to producing microalgal biofuel at a competitive price. Use of wastewater in algal cultivation has been very popular recently as freshwater and nutrients can be supplied at the same time and credits for wastewater treatment could be granted [4–6, 12, 15, 18, 29–31]. In addition, production of by-products, such as protein for animal feed, char for biofertilizers, and carbohydrates for fermentation, could help improve the overall economy of the algal biofuel production [50]. Revenues made by other co-products allow increased target oil price. Doubling the target algal oil price also doubles the limits for CAPEX and OPEX, refer Eq. (3). Therefore, even algal biofuel production facilities with high operating cost can achieve economic feasibility if additional revenue can be generated by other means.

Culturing microalgae in the ocean could be a way to alleviate the CAPEX and OPEX in algal biofuel production. In contrast to land-based culture systems, offshore algal culture systems do not require extensive land constructions, purchase of land, or expensive durable materials for construction because seawater supports the system. Moreover, seawater can be supplied on-site, eliminating the need for drilling water wells or installing long pipelines. Wastewater and flue gas can also be used in ocean-based algal culture systems especially when they are located near the coast for supply of CO₂ and other nutrients while removing pollutants as well [29–31, 51]. CO₂ can also be supplied in the form of sodium bicarbonate salt or concentrated solution [52, 53]. For offshore

microalgal cultivation far away from the coast, nutrients dissolved in seawater can be utilized by using technology such as semi-permeable membrane PBRs [27, 35]. In such case of relying on dissolved nutrients, obtaining high nitrogen and phosphorus supply rate will be important as CO₂ is relatively abundant in comparison to the others [27]. Culture mixing by harnessing the energy from ocean waves instead of the paddle wheels traditionally used in pond systems is also a potential advantage of use of ocean-based algal culture that leads to decreased power consumption, thereby lowering OPEX [28]. If the aforementioned advantages of ocean-based culture systems are effectively delivered, significant cost reductions would be possible.

Offshore cultivation of microalgae also brings challenges not present in land-based algal cultures. For instance, fouling is a prevailing phenomenon in marine environment that could negatively affect algal biomass productivity and needs to be dealt with [33]. In case of culturing marine microalgae in seawater, salts in the biomass could increase CAPEX and OPEX in the downstream processes. While salts in marine microalgae did not affect transesterification reaction [54], they might cause solid deposition and corrosion in the reactors [55]. On the contrary, using marine strain can bring advantages in the process as introduction of salt in hydrothermal liquefaction (HTL) yielded higher composition of hydrocarbon in bio-oil [56], and hydrothermal microwave processing showed better performance for marine microalgae than freshwater strains [57]. Costs for harvesting and transportation of produced biomass are also of concerns. Development of in situ harvest methods, such as floatation, for concentration and dewatering of algal biomass could reduce the cost for transportation [58]. At a full-scale, construction of an offshore platform adjacent to an offshore algal culture facility would be a more economic option, so that final products, algal biofuel and other byproducts, could be transported as how fossil fuels from offshore platforms are extracted and transported. As land-based open ponds and PBRs have been thoroughly studied and developed for decades, offshore culture systems would need to be extensively tested and carefully developed to become a viable option in large-scale algal biofuel production.

3.3 Potentials of utilizing marine resources to improve sustainability of microalgal biofuels

Resource requirements for global-scale microalgal biofuel production were assessed for each productivity case (Table 2). For the basic scenario (case 1), 0.12 ha, 291 m³ of freshwater, 2.4 t of carbon, 0.31 t of nitrogen, 0.07 t of phosphorus, and 0.04 t of potassium are needed for 1 TOE of microalgal biofuel. The area needed to replace 30% of annual global liquid transportation fuel (gasoline, diesel, and jet fuel) consumption ranged from 23 Mha to 100 Mha,

Table 2. Resource requirements for production of microalgal biofuel to replace 30% of global transportation fuel consumption.

	Case 1	Case 2	Case 3	Case 4
Area (Mha)	100	75	30	23
% of non-arable land	0.87	0.65	0.26	0.20
% of ocean area	0.27	0.21	0.08	0.06
Freshwater demand ^{a)} (km ³ ·y ⁻¹)	244	244	37	37
% of non-agricultural fresh-water consumption	21	21	3.2	3.2
Freshwater demand ^{b)} (km ³ ·y ⁻¹)	58	58	–	–
% of non-agricultural fresh-water consumption	5.0	5.0	–	–
Carbon demand (Mt·y ⁻¹)	1995	997	1995	997
% of CO ₂ emissions	5.8	2.9	5.8	2.9
Nitrogen demand (Mt·y ⁻¹)	259	130	259	130
% of N consumption	235	118	235	118
% of ocean inventory	0.04	0.02	0.04	0.02
Phosphorus demand (Mt·y ⁻¹)	57	29	57	29
% of P consumption	324	162	324	162
% of ocean inventory	0.06	0.03	0.06	0.03
Potassium demand (Mt·y ⁻¹)	37	18	37	18
% of K consumption	148	74	148	74

a) When freshwater is used for cultivation

b) When seawater is used for cultivation

accounting for 0.20–0.87% of the total non-arable land area, depending on the areal productivity. Because of the inherent nature of the culture systems, PBRs require much less freshwater (37 km³ y⁻¹) than ORPs (244 km³ y⁻¹). These values correspond to 3.2 and 21% of total non-agricultural freshwater consumption. Nutrient demands were lower when the lipid content was higher. When the lipid content was 50%, 997 Mt of carbon, 130 Mt of nitrogen, 29 Mt of phosphorus, and 18 Mt of potassium would be needed. The amounts of nutrients required for algal cultivation are doubled if the lipid content is 25%. When compared to the global consumption, 74–324% more nitrogen, phosphorus, and potassium must be produced to meet 30% of the global fuel demand. When the demand for carbon was compared to the world CO₂ emissions, 2.9–5.8% of CO₂ would be consumed for algal cultivation.

On the global scale, the area for algal cultivation is not a great concern. An area roughly equal to the land area of Egypt would suffice for cultivation of microalgae. However, evaluation of the freshwater and nutrient requirements indicates that algal biofuel may not be sustainable and would compete with agriculture for resources on a global scale. The main reason for the high water consumption in algal culture is the need to compensate for evaporation losses, especially in open culture systems [59]. Thus, the freshwater demand was substantially lower for cases with closed PBRs (fourth row in Table 2). Unlike traditional energy crops, many microalgae thrive in seawater. Therefore, if marine microalgae are cultivated using seawater for large-scale open cultures, the evaporation loss can be replenished continuously from the sea,

which would reduce the need for freshwater by 88% (fourth and sixth rows in Table 2) [59].

Nitrogen fertilizer can be produced from atmospheric nitrogen gas by chemical reactions. Therefore, if necessary, nitrogen fertilizer production can be expanded to meet the extra demand for algal biofuel production. However, the process consumes power and results in GHG emissions [60]; therefore, synthetic nitrogen should be the last choice when selecting the source of nitrogen. Other fertilizers pose a much severe problem. Phosphorus and potassium are finite underground resources like crude oil, and phosphorus reserves are being rapidly depleted [61]. As shown in Table 2, enormous amounts of phosphorus and potassium are required for biofuel production from microalgae. Use of these fertilizers for biofuels production will likely lead to food vs. fuel conflicts, which is contrary to the idea of using microalgae instead of conventional energy crops for biofuel production. Therefore, non-fertilizer nutrients must be utilized for algal cultures and nutrients should be reclaimed. Linking municipal or livestock wastewaters to algal cultivation is an excellent option as discussed above. HTL has recently been receiving a great deal of attention because of its potential for higher energy balance and nutrients recycling. One of the products of the HTL process is an aqueous phase (AP) containing the nutrients assimilated into the algal biomass, which could be used for growing microalgae [57, 62, 63]. However, growth inhibitors may also be present in the AP, requiring heavy dilution prior to use as a nutritional supplement to the culture medium [57]. In other studies, 50–75% of nutrients could be supplied using the AP [62, 63], but further improvements are required to close the loop.

Another approach to supply nutrition could be utilization of nutrients dissolved in seawater. The oceanic inventories of inorganic nitrogen and phosphorus in the ocean are approximately 660 and 93 billion tons, respectively [64, 65]. Potassium is far more abundant than other nutrients in seawater, and carbon is continuously replenished by dissolution of atmospheric CO₂. Even if the nutrients currently available in seawater are consumed for algal culture without replenishment or recycling, microalgal biofuel can be produced for several thousands of years. Using these vast amount of dissolved nutritional salts could alleviate the demand for extra fertilizer supply. However, the concentrations of nitrogen and phosphorus are insufficient to use seawater directly as a culture medium; therefore, methods to concentrate nutrients or microalgae, such as semi-permeable membranes, would be required to achieve significant algal biomass productivity [27, 35].

No biofuels can be sustainable if any parts of the biomass are to be wasted or any of the nutrients are to be continuously supplied. The reasons why we call the current economy as the fossil-based economy or the petroleum-based economy are (i) many commodities other than the energy are supplied from fossil resources and (ii)

every single molecule in the crude oil is consumed. A sustainable bio-based economy won't be realized until we find a way to close the loop by converting and/or recycling every atom in the biomass.

4 Concluding remarks

The global maximum microalgal biofuel productivity (when other substrates are sufficient and conditions are within the optimal growth range) is estimated at 3.2–14.8 TOE ha⁻¹ y⁻¹ with a global average of 8.4 TOE ha⁻¹ y⁻¹ when open ponds are used as the culture system and the lipid content of microalgae is 25%. Enhancements in the PE (from 3.1% PAR to 10.3% PAR) and lipid content (from 25 to 50%) could lead to increases of 233% and 33% in maximum biofuel productivity, respectively. Economic assessment showed that CAPEX and OPEX of an algal biofuel production facility should be considerably reduced while maintaining or increasing biofuel productivity. Production of co-products and convert/recycle every molecule in the biomass can also significantly improve the economy of algal biofuels, but since they would be produced in vast quantities, large markets need to be secured beforehand. For example, the bioplastic market is rapidly growing and estimated to reach 10 billion USD by 2020, while growth of the global fish feed market is projected to 123 billion USD by 2019. Demand for protein feeds for livestock is also estimated to be over 200 Mt y⁻¹. Offshore algal culture systems that do not require extensive land construction, are built with low-cost materials, use nutrients in wastewater or seawater, and utilize ocean waves for culture mixing can also be an option to substantially reduce CAPEX and OPEX in algal biofuel production. Furthermore, cultivation of microalgae in areas with high annual solar irradiance (e.g. Southeast Pacific Ocean) would help ensure high microalgal biofuel productivity.

Global-scale algal cultivation for biofuel production was not sustainable using conventional algal culture technologies. Indeed, enormous quantities of freshwater, nitrogen, phosphorus, and potassium comparable to the current global consumption would be needed to produce enough algal biofuel to meet 30% of the transportation fuel demand. Algal production will likely conflict with food production for resources. Cultivation of marine microalgae in seawater could easily alleviate the freshwater demand. Use of non-fertilizer nutrients, such as dissolved inorganic nutrients in seawater and wastewater, and reclaiming nutrients in algal biomass by a process like HTL would be necessary for sustainable production of algal biofuel.

Microalgae hold great potential for biofuel production, but mass production of algal fuel will require enormous amounts of resources. We showed that harnessing abundant marine resources could be a way to sustainably meet

resource requirements. As offshore microalgal cultivation is relatively a new technology, there are challenges and potential problems that need to be investigated and solved, including fouling, transportation of products, detailed financial analysis, ecological impacts, political issues, etc. Nevertheless, with extensive research and development (R&D) efforts, ocean-based algal culture systems would provide another option for sustainable and economic production of microalgae in the future.

This research was supported by a grant from the Marine Biotechnology Program (PJT200255, Development of Marine Microalgal Biofuel Production Technology) funded by the Ministry of Oceans and Fisheries, Korea. Authors are also grateful to the Manpower Development Program for Marine Energy from the same ministry. Hanwool Park was also supported by a NRF (National Research Foundation of Korea) Grant funded by the Korean Government (NRF-2013H1A2A1032623).

5 References

- [1] Koçar, G., Civaş, N., An overview of biofuels from energy crops: Current status and future prospects. *Renewable Sustainable Energy Rev.* 2013, 28, 900–916.
- [2] Bergthorson, J. M., Thomson, M. J., A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. *Renewable Sustainable Energy Rev.* 2015, 42, 1393–1417.
- [3] Chisti, Y., Constraints to commercialization of algal fuels. *J. Biotechnol.* 2013, 167, 201–214.
- [4] Mata, T. M., Martins, A. A., Caetano, N. S., Microalgae for biodiesel production and other applications: A review. *Renewable Sustainable Energy Rev.* 2010, 14, 217–232.
- [5] Rawat, I., Kumar, R. R., Mutanda, T., Bux, F., Biodiesel from microalgae: A critical evaluation from laboratory to large scale production. *Appl. Energy* 2013, 103, 444–467.
- [6] Slade, R., Bauen, A., Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Bio-mass Bioenergy* 2013, 53, 29–38.
- [7] Razeghifard, R., Algal biofuels. *Photosynth. Res.* 2013, 117, 207–219.
- [8] Richardson, J. W., Johnson, M. D., Zhang, X., Zemke, P. et al., A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability. *Algal Res.* 2014, 4, 96–104.
- [9] Moody, J. W., McGinty, C. M., Quinn, J. C., Global evaluation of biofuel potential from microalgae. *Proc. Natl. Acad. Sci. USA* 2014, 111, 8691–8696.
- [10] Chisti, Y., Biodiesel from microalgae beats bioethanol. *Trends Biotechnol.* 2008, 26, 126–131.
- [11] Zhang, Y., Liu, X., White, M. A., Colosi, L. M., Economic evaluation of algae biodiesel based on meta-analyses. *Int. J. Sustainable Energy* 2015, 1–13.
- [12] Lundquist, T. J., Woertz, I. C., Quinn, N., Benemann, J. R., A realistic technology and engineering assessment of algae biofuel production. *Energy Biosci. Inst.* 2010, 1–178.
- [13] Davis, R., Aden, A., Pienkos, P. T., Techno-economic analysis of autotrophic microalgae for fuel production. *Appl. Energy* 2011, 88, 3524–3531.
- [14] Wang, T., Yabar, H., Higano, Y., Perspective assessment of algae-based biofuel production using recycled nutrient sources: The case of Japan. *Bioresour. Technol.* 2013, 128, 688–696.
- [15] Ramachandra, T., Madhab, M. D., Shilpi, S., Joshi, N., Algal biofuel from urban wastewater in India: Scope and challenges. *Renewable Sustainable Energy Rev.* 2013, 21, 767–777.
- [16] Rodolfi, L., Chini Zittelli, G., Bassi, N., Padovani, G. et al., Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor. *Biotechnol. Bioeng.* 2009, 102, 100–112.
- [17] Huntley, M. E., Redalje, D. G., CO₂ mitigation and renewable oil from photosynthetic microbes: A new appraisal. *Mitigation Adaptation Strategies Global Change* 2007, 12, 573–608.
- [18] Choi, J., Kim, B., Kang, Z., Oh, H., Kim, H., Biodiesel production and nutrients removal from piggery manure using microalgal small scale raceway pond (SSRP). *Korean J. Environ. Biol.* 2014, 32, 26–34.
- [19] Quinn, J. C., Catton, K., Wagner, N., Bradley, T. H., Current large-scale US biofuel potential from microalgae cultivated in photobioreactors. *Bioenergy Res.* 2012, 5, 49–60.
- [20] Feng, P., Deng, Z., Hu, Z., Fan, L., Lipid accumulation and growth of *Chlorella zofingiensis* in flat plate photobioreactors outdoors. *Bioresour. Technol.* 2011, 102, 10577–10584.
- [21] Williams, P. J. le B., Laurens, L. M., Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy Environ. Sci.* 2010, 3, 554–590.
- [22] Chen, C.-Y., Chang, H. Y., Lipid production of microalga *Chlorella sorokiniana* CY1 is improved by light source arrangement, bioreactor operation mode and deep-sea water supplements. *Biotechnology J.* 2016, 11, 356–362.
- [23] Liu, Z., Liu, S., Wang, K., Luo, X., Status and prospects for phosphor-based white LED packaging. *Front. Optoelectron. China* 2009, 2, 119–140.
- [24] Zhu, X.-G., Long, S. P., Ort, D. R., What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Curr. Opin. Biotechnol.* 2008, 19, 153–159.
- [25] Blanken, W., Cuaresma, M., Wijffels, R. H., Janssen, M., Cultivation of microalgae on artificial light comes at a cost. *Algal Res.* 2013, 2, 333–340.
- [26] Weyer, K. M., Bush, D. R., Darzins, A., Willson, B. D., Theoretical maximum algal oil production. *Bioenergy Res.* 2010, 3, 204–213.
- [27] Kim, Z.-H., Park, H., Ryu, Y.-J., Shin, D.-W. et al., Algal biomass and biodiesel production by utilizing the nutrients dissolved in seawater using semi-permeable membrane photobioreactors. *J. Appl. Phycol.* 2015, 27, 1763–1773.
- [28] Kim, Z.-H., Park, H., Hong, S.-J., Lim, S.-M., Lee, C.-G., Development of a floating photobioreactor with internal partitions for efficient utilization of ocean wave into improved mass transfer and algal culture mixing. *Bioprocess Biosyst. Eng.* 2016, 39, 713–723.
- [29] Wiley, P. E., Microalgae cultivation using offshore membrane enclosures for growing algae (OMEGA). *J. Sustainable Bioenergy Syst.* 2013, 3, 18–32.
- [30] Novoveská, L., Zapata, A. K. M., Zabolotney, J. B., Atwood, M. C., Sundstrom, E. R., Optimizing microalgae cultivation and wastewater treatment in large-scale offshore photobioreactors. *Algal Res.* 2016, 18, 86–94.
- [31] McConnell, B., Farag, I. H., *11AICHE - 2011 AICHE Annual Meeting, Conference Proceedings* 2011.
- [32] Trent, J., Wiley, P., Tozzi, S., McKuin, B., Reinsch, S., Research Spotlight: The future of biofuels: Is it in the bag? *Biofuels* 2012, 3, 521–524.
- [33] Harris, L., Tozzi, S., Wiley, P., Young, C. et al., Potential impact of biofouling on the photobioreactors of the Offshore Membrane Enclosures for Growing Algae (OMEGA) system. *Bioresour. Technol.* 2013, 144, 420–428.

- [34] Dogaris, I., Welch, M., Meiser, A., Walmsley, L., Philippidis, G., A novel horizontal photobioreactor for high-density cultivation of microalgae. *Bioresour. Technol.* 2015, *198*, 316–324.
- [35] Lee, S. Y., Kim, Z. H., Oh, H. Y., Choi, Y. et al., Fabric-hydrogel composite membranes for culturing microalgae in semipermeable membrane-based photobioreactors. *J. Polym. Sci. Part A: Polym. Chem.* 2016, *54*, 108–114.
- [36] Norsker, N.-H., Barbosa, M. J., Vermuë, M. H., Wijffels, R. H., Microalgal production—a close look at the economics. *Biotechnol. Adv.* 2011, *29*, 24–27.
- [37] Mandalam, R. K., Palsson, B., Elemental balancing of biomass and medium composition enhances growth capacity in high-density *Chlorella vulgaris* cultures. *Biotechnol. Bioeng.* 1998, *59*, 605–611.
- [38] Morweiser, M., Kruse, O., Hankamer, B., Posten, C., Developments and perspectives of photobioreactors for biofuel production. *Appl. Microbiol. Biotechnol.* 2010, *87*, 1291–1301.
- [39] Suali, E., Sarbaty, R., Conversion of microalgae to biofuel. *Renewable Sustainable Energy Rev.* 2012, *16*, 4316–4342.
- [40] Abomohra, A. E.-F., Wagner, M., El-Sheekh, M., Hanelt, D., Lipid and total fatty acid productivity in photoautotrophic fresh water microalgae: Screening studies towards biodiesel production. *J. Appl. Phycol.* 2013, *25*, 931–936.
- [41] Bertozzini, E., Galluzzi, L., Ricci, F., Penna, A., Magnani, M., Neutral lipid content and biomass production in *Skeletonema marinoi* (Bacillariophyceae) culture in response to nitrate limitation. *Appl. Biochem. Biotechnol.* 2013, *170*, 1624–1636.
- [42] Griffiths, M. J., van Hille, R. P., Harrison, S. T., Lipid productivity, settling potential and fatty acid profile of 11 microalgal species grown under nitrogen replete and limited conditions. *J. Appl. Phycol.* 2012, *24*, 989–1001.
- [43] Schlagemann, P., Göttlicher, G., Dillschneider, R., Rosello-Sastre, R., Posten, C., Composition of algal oil and its potential as biofuel. *J. Combust.* 2012, *2012*.
- [44] Kwiatkowski, J. R., McAloon, A. J., Taylor, F., Johnston, D. B., Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Ind. Crops Prod.* 2006, *23*, 288–296.
- [45] Goldemberg, J., Ethanol for a sustainable energy future. *Science* 2007, *315*, 808–810.
- [46] Acevedo, J. C., Hernández, J. A., Valdés, C. F., Khanal, S. K., Analysis of operating costs for producing biodiesel from palm oil at pilot-scale in Colombia. *Bioresour. Technol.* 2015, *188*, 117–123.
- [47] You, Y.-D., Shie, J.-L., Chang, C.-Y., Huang, S.-H. et al., Economic Cost Analysis of Biodiesel Production: Case in Soybean Oil†. *Energy Fuels* 2007, *22*, 182–189.
- [48] Liang, F., Xia, X., Long-term trends in solar radiation and the associated climatic factors over China for 1961–2000. *Ann. Geophys.* 2005, *23*, 2425–2432.
- [49] Cysewski, G. R., 2nd Algae World. Brussels, Belgium, 31th May–1st June 2010.
- [50] Hariskos, I., Posten, C., Biorefinery of microalgae – opportunities and constraints for different production scenarios. *Biotechnol. J.* 2014, *9*, 739–752.
- [51] Yen, H.-W., Ho, S.-H., Chen, C.-Y., Chang, J.-S., CO₂, NO_x and SO_x removal from flue gas via microalgae cultivation: A critical review. *Biotechnol. J.* 2015, *10*, 829–839.
- [52] Cho, Y., Shin, D.-W., Lee, S., Jeon, H. et al., Investigation of microalgal growth, *Tetraselmis* sp. KCTC12432BP by supplying bicarbonate on the ocean cultivation. *J. Mar. Biosci. Biotechnol.* 2014, *6*, 118–122.
- [53] Chi, Z., O’Fallon, J. V., Chen, S., Bicarbonate produced from carbon capture for algae culture. *Trends Biotechnol.* 2011, *29*, 537–541.
- [54] Velasquez-Orta, S. B., Lee, J. G. M., Harvey, A. P., Evaluation of FAME production from wet marine and freshwater microalgae by in situ transesterification. *Biochem. Eng. J.* 2013, *76*, 83–89.
- [55] Yan, J., Shamim, T., Chou, S. K., Li, H. et al., Clean, efficient and affordable energy for a sustainable future: The 7th International Conference on Applied Energy (ICAE2015) Thermochemical Conversion of Microalgae: Challenges and Opportunities. *Energy Procedia* 2015, *75*, 819–826.
- [56] Sanguineti, M. M., Hourani, N., Witt, M., Sarathy, S. M. et al., Analysis of impact of temperature and saltwater on *Nannochloropsis salina* bio-oil production by ultra high resolution APCI FT-ICR MS. *Algal Res.* 2015, *9*, 227–235.
- [57] Biller, P., Friedman, C., Ross, A. B., Hydrothermal microwave processing of microalgae as a pre-treatment and extraction technique for bio-fuels and bio-products. *Bioresour. Technol.* 2013, *136*, 188–195.
- [58] Ndikubwimana, T., Chang, J., Xiao, Z., Shao, W. et al., Flotation: A promising microalgae harvesting and dewatering technology for biofuels production. *Biotechnol. J.* 2016, *11*, 315–326.
- [59] Harto, C., Meyers, R., Williams, E., Life cycle water use of low-carbon transport fuels. *Energy Policy* 2010, *38*, 4933–4944.
- [60] Johnson, M. C., Palou-Rivera, I., Frank, E. D., Energy consumption during the manufacture of nutrients for algae cultivation. *Algal Res.* 2013, *2*, 426–436.
- [61] Cordell, D., Drangert, J.-O., White, S., The story of phosphorus: Global food security and food for thought. *Global Environ. Change* 2009, *19*, 292–305.
- [62] Alba, L. G., Torri, C., Fabbri, D., Kersten, S. R., Brilman, D. W. W., Microalgae growth on the aqueous phase from hydrothermal liquefaction of the same microalgae. *Chem. Eng. J.* 2013, *228*, 214–223.
- [63] Barreiro, D. L., Bauer, M., Hornung, U., Posten, C. et al., Cultivation of microalgae with recovered nutrients after hydrothermal liquefaction. *Algal Res.* 2015, *9*, 99–106.
- [64] Gruber, N., The marine nitrogen cycle: Overview and challenges, in: Capone, D. G., Bronk, D. A., Mulholland, M. R., Carpenter, E. J. (Eds.), *Nitrogen In The Marine Environment, 2nd Edn.*, Elsevier 2008, 1–50.
- [65] Paytan, A., McLaughlin, K., The oceanic phosphorus cycle. *Chem. Rev.* 2007, *107*, 563–576.



Cover illustration

This special issue, in collaboration with the Asian Federation of Biotechnology and edited by Professors Hyung Joon Cha, Noriho Kamiya and S. Vikineswary Sabaratnam, covers the most advanced biotech research from Asian Congress of Biotechnology 2015. This issue includes articles on drug delivery, enzyme engineering, cellular therapy, biosensors, etc. The 30Kc19 protein derived from the silkworm hemolymph consists of two domains, which are 30Kc19 α (blue) and 30Kc19 β (red). The cover image shows that 30Kc19 α has multifunctional properties, which are cell penetration, protein stabilization, and cargo delivery. The Image is provided by Jina Ryu, Hyoju Kim, Hee Ho Park, Hong Jai Lee, Ju Hyun Park, Won Jong Rhee and Tai Hyun Park authors of "Protein-stabilizing and cell-penetrating properties of α -helix domain of 30Kc19 protein" (<http://dx.doi.org/10.1002/biot.201600040>).

Biotechnology Journal – list of articles published in the November 2016 issue.

Editorial

Asian Congress on Biotechnology 2015

Hyung Joon Cha, Noriho Kamiya and
S. Vikineswary Sabaratnam

<http://dx.doi.org/10.1002/biot.201600650>

Commentary

Therapeutic effects of stem cells on ischemic stroke were confirmed in an improved photothrombotic mouse model

I-Ming Chu

<http://dx.doi.org/10.1002/biot.201600414>

Review

Solid-in-oil nanodispersions for transdermal drug delivery systems

Momoko Kitaoka, Rie Wakabayashi, Noriho Kamiya
and Masahiro Goto

<http://dx.doi.org/10.1002/biot.201600081>

Review

Design of nanoscale enzyme complexes based on various scaffolding materials for biomass conversion and immobilization

Jeong Eun Hyeon, Sang Kyu Shin and Sung Ok Han

<http://dx.doi.org/10.1002/biot.201600039>

Research Article

Effect of human mesenchymal stem cell transplantation on cerebral ischemic volume-controlled photothrombotic mouse model

Yun-Kyong Choi, Enerelt Urnukhsaikhan, Hee-Hoon Yoon,
Young-Kwon Seo and Jung-Keug Park

<http://dx.doi.org/10.1002/biot.201600057>

Research Article

Multiplex 16S rRNA-derived geno-biochip for detection of 16 bacterial pathogens from contaminated foods

Hwa Hui Shin, Byeong Hee Hwang and Hyung Joon Cha

<http://dx.doi.org/10.1002/biot.201600043>

Research Article

Fabrication of multilayered vascular tissues using microfluidic agarose hydrogel platforms

Keita Kinoshita, Masaki Iwase, Masumi Yamada,
Yuya Yajima and Minoru Seki

<http://dx.doi.org/10.1002/biot.201600083>

Research Article

Enhanced production of 2,3-butanediol in pyruvate decarboxylase-deficient *Saccharomyces cerevisiae* through optimizing ratio of glucose/galactose

Eun-Ji Choi, Jin-Woo Kim, Soo-Jung Kim, Seung-Oh Seo,
Stephan Lane, Yong-Cheol Park, Yong-Su Jin and Jin-Ho Seo

<http://dx.doi.org/10.1002/biot.201600042>

Research Article

Ex vivo culture of circulating tumor cells using magnetic force-based coculture on a fibroblast feeder layer

Shuhei Yamamoto, Kazunori Shimizu, Jiahui Fei, Hiroji
Iwata, Mina Okochi, Hayao Nakanishi and Hiroyuki Honda

<http://dx.doi.org/10.1002/biot.201600084>

Research Article

Protein-stabilizing and cell-penetrating properties of α -helix domain of 30Kc19 protein

Jina Ryu, Hyoju Kim, Hee Ho Park, Hong Jai Lee,
Ju Hyun Park, Won Jong Rhee and Tai Hyun Park

<http://dx.doi.org/10.1002/biot.201600040>

Research Article

Enzymatically prepared redox-responsive hydrogels as potent matrices for hepatocellular carcinoma cell spheroid formation

Kousuke Moriyama, Shono Naito, Rie Wakabayashi, Masahiro Goto and Noriho Kamiya

<http://dx.doi.org/10.1002/biot.201600087>

Research Article

Theoretical calculations on the feasibility of microalgal biofuels: Utilization of marine resources could help realizing the potential of microalgae

Hanwool Park, Choul-Gyun Lee

<http://dx.doi.org/10.1002/biot.201600041>