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Luminescent solar concentrator panels for increasing the efficiency of mass microalgal production

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ABSTRACT

Raceway open ponds are preferred cultivation system for mass algal commodity production. For operational reasons, large-scale raceway ponds must be operated at a depth greater than 20 cm meaning that algal cultures are normally light limited as light cannot penetrate into the depth below 5 cm. For the efficient distribution of light into the culture, different light delivery systems such as temporal and spatial have been proposed. If the proper mixing created, the flashing light effect can be created and that would result in a significant increase in biomass productivity. However, to date, this method has not been achieved in outdoor raceway open ponds. On the other hand, spatial light dilution systems are found to be more effective and economical that temporal light dilution systems. Among spatial dilution systems, luminescent solar concentrator (LSC) panels have a potential to be commercialized for mass microalgae production. Luminescent solar concentrators combine spectrum shifting properties with spatial dilution to channel the light into the culture where it is needed. There is also the possibility of electricity production as well as higher algal biomass production when using LSC panels in open ponds or PBRs. Additionally, compared to other proposed methods, the lower capital cost can be expected when using LSCs in algal cultivation systems as there is no need to use a solar tracking system to track the sun. In this review article, the effects of photolimitation, photosaturation and, photoinhibition in concentrated microalgal cultures, as well as the impact of applying different light distribution systems on the biomass productivity and photosynthetic efficiency as a result of having more uniform distribution of light into the culture, have been outlined.

1. Introduction

Since 1965, microalgae have been grown commercially in various fields such as high value products (e.g., β-carotene and astaxanthin), human and animal nutrition, pharmacy and cosmetics [1–3]. Further, microalgae have the potential to be commercialized for commodity products such as biofuel and food [4,5], as well as a tool for carbon dioxide bioremediation [6,7].

There are two main proposed microalgae cultivation systems, raceway open ponds and closed photobioreactors. To date, paddle wheel driven raceway ponds are found to be the most cost-effective cultivation systems, especially for large scale mass cultivation of commodity products [8]. Achieving higher yields per illuminated surface area and culture volume as well as shorter specific growth rates are primary goals in microalgal cultivation [9]. Large scale open ponds must be operated in depth of 20–30 cm, however, there is more availability of light into the depth of shallower ponds [10]. Solar energy plays a significant role in the growth and productivity of microalgae [11]. In any cultivation system, culture productivity depends heavily on capturing light energy efficiently while the growth of microalgae is usually saturated at an irradiance of around 200 μmol m^{-2} s^{-1}, which is about 1/10 of the maximum irradiance of a summer day [1,12]. The main aim of any algal grower is to achieve maximum yield of targeted product at the shortest doubling time resulting in the highest productivity [13]. Considering that one would have to operate the culture at specific depth [14] and biomass concentrations are normally set at the highest achievable yield [15], there is a very limited control on light availability to the cell in open ponds. Thus, using a light delivering system

Abbreviations: LSC, Luminescent solar concentrator; PBR, Photobioreactor; LSE, light saturation effect; MPE, Maximum photosynthetic efficiency; PAR, Photosynthetic active radiation; PE, Photosynthetic efficiency; PPFD, Photosynthetic photon flux density; LDOP, Light diffusing optical fibers; PMMA, Polymethyl methacrylate

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for algal cultivation systems with poor light availability to algal cells such as raceway open ponds is demanding.

There have been several systems for increasing light irradiance inside the microalgae cultures such as temporal light dilution [16], Fresnel lenses [17], optical fibers [18] and, luminescent solar concentrators [19]. These systems are discussed in details in the following sections. The overarching goal of this review is to evaluate and compare various light distribution designs for photobioreactors and open ponds aiming to deliver incident light to microalgal cells more efficiently. The main target is to improve photosynthetic efficiency resulting in an increase of microalgal productivity. In addition, the effects of photolimitation, photosaturation and, photoinhibition in concentrated microalgal cultures are discussed.

2. Microalgae, light and, photosynthesis

Sun supplies an enormous amount of energy to the Earth with radiant power of 3.846×10^{26} W. The visible spectrum (390–750 nm), the infrared (IR) (0.7–300 mm) and, ultraviolet (UV) radiation (10–390 nm) account for 52%, 42% and, 6% of solar energy [20]. Photosynthetic active radiation (PAR), 400–700 nm, is the visible portion of light delivering around 3.9×10^6 EJ each year to the Earth [21] which can be absorbed by photosynthetic pigments [22]. The PAR contains 43% of the total solar energy (AM1.5) and mainly includes the visible spectrum [20]. The Earth is covered by green plants which transfer light energy into chemical energy via photosynthesis. However, the overall photosynthesis conversion efficiency, the ability to convert light energy into biomass, is very low (1–2%) to make up the human demand for energy. It is to be noted that the maximum theoretical PE is 8–12% [21].

In the process of photosynthesis, photosynthetic pigments are responsible for capturing light and using the absorbed energy to generate NADPH and ATP and convert CO_2 and water to carbohydrate [23]. Also, producing one mole of carbohydrate (CH_2O) and one mole O_2 requires 8 moles of light photons in the photosynthesis process [24]. Thus, the maximum (theoretical) quantum yield can be the fixation of 0.125 mol CO_2 (or oxygen evolution) per mole photon absorbed [25]. Considering that one mole of photons in the PAR region has the averaged energy content of 217 kJ, producing one mole of CH_2O requires the potential captured light energy of 1744 kJ. Knowing the fact that the energy contained in one mole of CH_2O is about 467 kJ and, 46 kJ $mole^{-1}$ PAR photons is the amount of energy lost as a result of PAR degradation to excitation energy at 700 nm (21% of absorbed PAR), the maximum theoretical photosynthetic solar energy conversion can be 12% [26]. Nevertheless, the maximum achieved photosynthetic efficiency of 3% has been reported for some microalgae species [27]. Such a low efficiency is due to loss of photons by reflection, respiration, photosaturation and, photoinhibition [26].

Three major pigment groups present in microalgae are chlorophylls, carotenoids and phycobilins with chlorophyll *a* present in all species [28]. These pigments are responsible for absorbing light in different parts of PAR. Chlorophylls absorb blue light (450–475 nm) and red light (630–680 nm) [28] and carotenoids (e.g., α- and β-carotenes, xanthophylls, lutein, and fucoxanthin) absorb light between 400 and 550 nm spectra [29,30]. On the other hand, phycobilins absorption is mainly between 500 and 650 nm [29].

The quantum rate captured from the light source, which affects the rate of microalgal photosynthesis, is determined by light absorption properties of microalgae, as well as light quality and quantity [24]. The efficiency of photosynthesis is microalgal species specific. Photosynthetic biomass productivity is also a function of photosynthetic efficiency [30]. The photosynthetic rate is proportional to the captured photon rate and the efficiency of photosynthetic reactions to convert the absorbed light into the chemical energy. The photosynthesis can be photolimited, photosaturated or photoinhibited region [26,31,32].

In well-mixed concentrated microalgal cultures, there is a complicated light field to which microalgae cells are exposed. In that light regime, light is declining exponentially from full sunlight at the surface to darkness at the depth according to the Lambert–Beer law [33]. In a concentrated microalgal culture, light can be categorized into four main zones (Fig. 1) [26]:

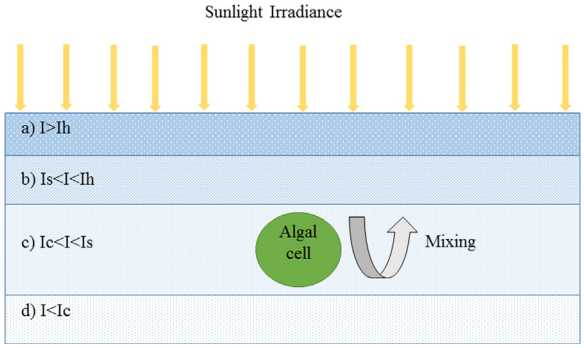

Fig. 1. Light zones in high concentrated algal culture. a) The zone where photoinhibition occurs, b) The light saturated zone where the maximum photosynthetic rate (Pmax) is achieved, c) The light limited zone where irradiance is lower than saturation point and c) The dark zone where photosynthesis does not occur [26].

a) Photoinhibited region where the amount of light received at the surface is far greater than light saturation (I_s) resulting in photoinhibition;
b) In the light saturated zone where the maximum photosynthetic rate (P_{max}) is achieved and irradiance is at I_s;
c) In the light limited zone where light is below I_s but above compensation light (I_c). In this condition, maximum light efficiency is achieved;
d) In the dark zone where net positive photosynthesis does not occur as irradiance is below I_c.

It is also noteworthy to mention that penetration of light varies with wavelength. For instance, green light penetrates into an algal culture 20-times more than blue and red light which are more important for photosynthesis than the green light (Fig. 2) [34]. Fig. 2 shows three wavelength region (a) the blue region in which 440 nm is absorbed by chlorophylls and carotenoids; (b) the green region, which there is no absorption by chlorophyll and carotenoids; and, (c) the red light region,

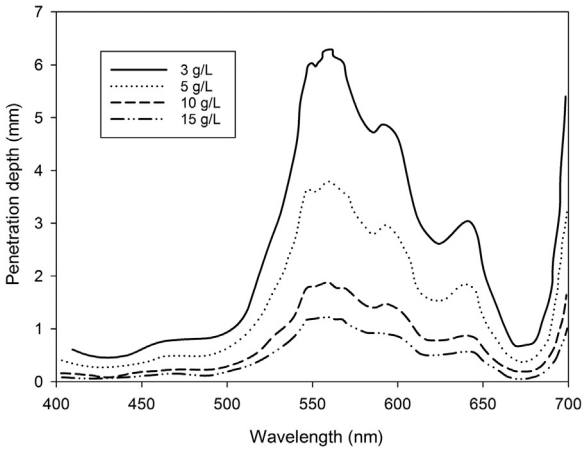

Fig. 2. Penetration depth* spectra in Nannochloropsis sp. as a function of cell density in a 200 L flat plate glass photobioreactor, with a 10 cm light-path. *Light penetration depth was calculated from the attenuation coefficient of down-welling irradiance which is defined as the depth in which down-welling irradiance decreased tenfold.
Reproduced from [35].

which represents chlorophyll absorption at 678 nm [35]. Obviously, penetration of green light is much deeper (20 times) than blue and red light. However, the green light is poorly absorbed by microalgae cells (Fig. 2). Therefore, green light can play a significant role in concentrated algal cultures where there is not enough light available for cells and thereby, increasing the photic volume in the reactor [36].

2.1. Photolimitation

Considering that light is strongly attenuated in concentrated microalgal cultures, its availability is not solely determined by incident radiation (I_0) on the reactor surface [31]. Photolimitation stems from inadequate irradiance and, thus, microalgal cells will not receive enough irradiance resulting in low areal algal biomass productivity, especially in open ponds. Photolimitation can be reduced by increasing the input irradiance and decreasing the culture depth [29]. For instance, Moheimani and Borowitzka [37] showed that by reducing open pond depth from 21 to 13 cm in autumn, *Pleurochrysis carterae* productivity could be increased over fivefold from 0.012 $g\,l^{-1}\,d^{-1}$ to 0.069 $g\,l^{-1}\,d^{-1}$.

In the region where light is limited, photosynthesis is linearly proportional to irradiance and, the maximum photosynthesis rate could be achieved in this region [38]. The maximum efficiency of light conversion into biomass is determined in the initial part of the PI curve (α) (Fig. 3). The maximum quantum yield of photosynthesis is also determined by the ratio between photosynthesis and irradiance in this region of the PI curve [39]. If α is measured in a very concentrated culture (all light is absorbed), it can be considered as the measured absorbed light and thus, the maximum quantum yield of photosynthesis [26].

2.2. Photosaturation

Photosaturation of microalgal cells occurs when light irradiance increases and microalgal cells cannot absorb the excess of photons which leads to no increase in photosynthesis. At light-saturated region, the number of photons absorbed by chlorophyll is higher than the number of electrons transferred from water to CO_2 and, consequently, the photosynthetic rate is limited. Thus, the rate of light conversion efficiency into chemical energy declines at the end of the linear region ending up to the light saturated region of the PI-curve (Fig. 3) [26]. There is a point (I_k), interception of α and P_{max}, where irradiance is saturating and photosynthesis is light saturated indicating the photoacclimation status (Fig. 3) [32].

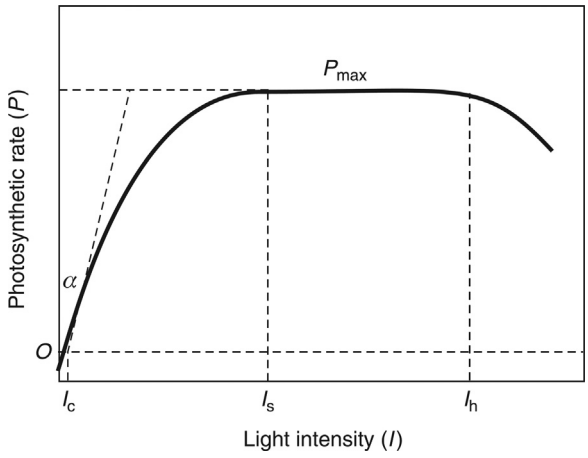

Fig. 3. PI curve that is the response of light to photosynthesis. The maximum light utilization efficiency is shown as α which is the initial slope of the PI-curve. Ic, light compensation point; Is, light saturation intensity; Ih, the light intensity at which photoinhibition occurs. (Copied from [36]. with permission).

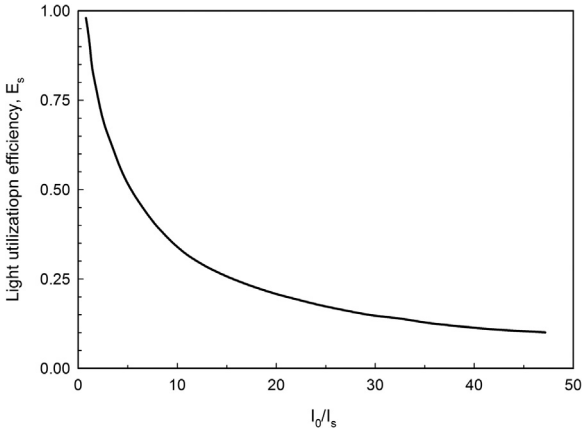

Fig. 4. Light utilization efficiency (ES) based on Bush equation (Eq. (1)) in a dense microalgae culture.
Reproduced from [40].

The maximum photosynthetic efficiency is determined by photosaturation or light saturation effect (LSE) in outdoor concentrated microalgal cultures. The LSE can be represented by the 'Bush equation' [40]:

$$E_s = \frac{I_s}{I_0}\left[\left(ln\frac{I_0}{I_s}\right)+1\right]. \quad (1)$$

where E_s is the light utilization efficiency, I_s is the light saturated point and, I_0 is the incident irradiance. The 'light utilization efficiency' is based on the amount of light utilized by the microalgal cells and the total irradiance (Fig. 4) [40]. High E_S can be potentially attained at low irradiances, but at high I_0/I_S ratios, E_S declines rapidly (Fig. 4). Thus, the value I_0 is the main factor for determining the E_s in an outdoor algal culture. For example, at I_0/I_S of 20, E_S is approximately 0.2 and, thus, light utilization efficiency is about 20%. It can be simply concluded that a lower ratio of I_0/I_S is desirable to have higher E_S. I_S is crucially important to determine the productivity of outdoor algal cultures and it is highly advantageous to grow microalgal species with high Is values [40]. Nonetheless, the saturation irradiance of the most marine algae is below 100 $\mu mol\,m^{-2}\,s^{-1}$ (~5% full sunlight) [26].

The light saturation effect would highly alleviate the photosynthetic efficiency of an outdoor mass culture of algae illuminated under full sunlight. Table 1 summarises the minimum energy losses of total sunlight irradiance in an outdoor microalgae culture from the beginning of receiving light by microalgae cells to carbohydrate formation. The actual photosynthetic efficiency of 7% of PAR has been reported at irradiance around half of the solar intensity [41]; however, several microalgae species have shown the photosynthetic efficiencies of up to 24% of PAR (11% of total solar radiation) [42].

Table 1
Minimum energy losses of total incident solar radiation in microalgae mass culture (Modified from [26]).

Minimum energy losses	Energy remaining (%)
Total incident solar radiation	100
Radiation outside PAR (55%)	45
Degradation of absorbed PAR photons to excitation energy at 700 nm (21%)	35.6
Conversion of excitation energy at 700 nm to the chemical energy of glucose (65%)	12.4 (Maximum photosynthetic efficiency)
Reflection (10%)	11.2
Respiration (20%)	9
Photosaturation and photoinhibition (40%)	5.4

2.3. Photoinhibition

Photoinhibition (I_h) is defined as a decrease of photosynthesis. It also results in declining maximum quantum yield of photosynthesis, light conversion efficiency and, the rate of photosynthesis mainly due to exposure of cells to high irradiance [43]. Photosynthetic capacity is also reduced by photoinhibition due to damage caused by high irradiance [44]. In other words, photoinhibition occurs when the irradiance is higher than the light saturated irradiance and, then, photosynthesis is less than P_{max} [45,46]. Photoinhibition depends on both light intensity and duration of light exposure. In many microalgae species, irradiances in the range of 100–200 μmol photons m^{-2} s^{-1} (approximately 10% of full sunlight) can cause photoinhibition [25].

Photoinhibition is due to the inactivation of reaction centers and is one of the most important problems for achieving high photosynthetic efficiency (PE) in outdoor algal cultures [26]. Grobbelaar [11] observed not only photoinhibition could reduce areal production rates by up to 30%, but also more than 60% of the reaction centers could become inactive by photoinhibition in a low density culture [11].

Photoinhibition can be controlled by:

a) Increasing biomass concentration: Richmond [47] showed that increasing biomass concentration in high density mass culture exposed to high light irradiance reduces photoinhibition;
b) Increasing the cycling between the light and dark zones by better mixing: Qiang and Richmond [48] increased the rate of mixing of *Spirulina* culture in a 2.5 L flat plate PBR from 0.6 vvm (L air per L culture per min) to 2.1 vvm and 4.2 vvm at a concentrated culture with biomass concentration of 5 g l^{-1}. They found that biomass productivity increased from 55 mg l^{-1} h^{-1} to 110 mg l^{-1} h^{-1} at 500 μ mol m^{-2} s^{-1}. Moreover, for the highest photosynthetic flux density (PFD) used, i.e., 1800 μmol m^{-2} s^{-1}, biomass productivity of cell mass obtained at this energy flux indicated a sensitive response to the rate of mixing; an increase in mixing rate from the minimal 0.6–4.2 vvm increased biomass productivity from 90 mg l^{-1} h^{-1} to 400 mg l^{-1} h^{-1} [48];
c) The use of intermittent light pulses: this method contains using a system to provide intermittent light irradiance. However, this approach can be useful for microalgae cultures with low cell densities where there is no mutual shading effect [49]. This method is most likely not going to be useful for mass algal cultures where achieving high productivity is the main objective as mutual shading increases, and consequently, there is less availability of light to algal cells [50].
d) The use of a continuous light source and moving the cells in and out in the illuminated region at a high frequency. By having high frequency, the illuminated cells will be replaced by dark cells and more cells, specifically in a concentrated culture, are exposed to flashes of light per unit time [36];
e) The use of microalgae species with a shorter antenna [51–53]. The photon absorption in a microalgae photosynthetic system with less light harvesting chlorophyll is fewer at a high light intensity, and thus, photon waste is also fewer [54,55] and;
f) The use of filters to remove unnecessary light wavelengths and pick specific useful wavelength for microalgae, thus reducing the total light irradiance [29]. Vadiveloo et al. [12] investigated the effect of spectrally limited light on the growth and photosynthesis rate *Nannochloropsis sp* using filters on top of the microalgae cultures. They found the highest specific growth rate of 0.30 d^{-1} under pink light and the highest biomass productivity of 1.93 mg L^{-1} d^{-1} (μmol photons m^{-2} s^{-1})$^{-1}$ under blue light for *Nannochloropsis sp*. [12]. The advantage of this system on microalgae culture was to select the particular wavelength to increase the biomass productivity as well as the potential ability to use the remainder wavelength for electricity production.

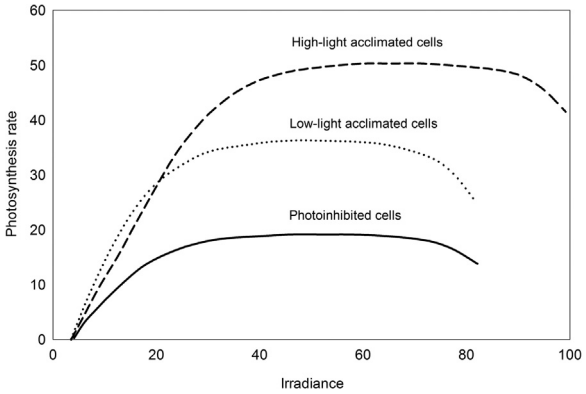

Fig. 5. The effect of photoinhibition and photoacclimation to low light in dense algal cultures on the light-response curve of photosynthesis.
Reproduced from [26].

2.4. Photoacclimation

Photoacclimation is a physiological response of phototrophic microalgae to changes in light intensity which happens in relatively short periods of time [50,56]. In mass microalgal cultures, acclimation of microalgal cells to high light depends on biomass yield, depth of the culture and, mixing rate [57]. The main problem in concentrated cultures is that cells do not receive enough light most of the time during the growth period and consequently, a very large antenna will be assembled due to low light acclimation. This is due to either producing photosynthetic unit (PSU) size in a larger size or higher number within the cell [32]. This results in a significant attenuation of light into the depth of the culture in which there is a very complex irradiance regime due to different culture depth, cell concentration and, mixing rate [58]. During photoacclimation, the quantum efficiency increases when irradiance decreases, but I_k and P_{max} decline (Fig. 5). This leads to a lower capacity to use high irradiances efficiently. The microalgal cells adapted to low light due to self shading-effect, absorb photons in large excess when they are in the irradiated layers, and then, there is a three possible consequences: a) they cannot use the excess of light efficiently and waste it as they are photosaturated; b) they may be photoinhibited; and c) they do not allow light to penetrate to the cells at the depth due to the shading effect [26]. This is the reason that productivity increases minimally while irradiance increased significantly even for algal cultures operated at optimum conditions. Interestingly, high-light adapted microalgae cells can re-adapt to low light condition quickly [34].

Torzillo et al. [57] carried out an outdoor experiment on the mass culture of *Phaeodactylum tricornutum* grown at a closed tubular photobioreactor at two biomass concentrations (0.3 and 0.6 g l^{-1}) to study the photoacclimation of *P. tricornutum*. The highest stress occurred for cultures grown at 0.3 g l^{-1}. As a result of that, photosynthesis parameters and chlorophyll fluorescence were changed dramatically, and areal productivity also decreased significantly while more concentrated cultures (0.6 g l^{-1}) did not show considerable changes in the photosynthetic parameters. They concluded that high-irradiance stress affected the diadinoxanthin cycle negatively and increased non-photochemical quenching, which lowered biomass productivity in the less concentrated culture [57].

3. Light and microalgae growth

3.1. Microalgal irradiance-growth model

In recent years, several microalgal irradiance-growth and productivity models have been developed [59,60]. The light availability of microalgal cells inside a culture depth determines the productivity. The PAR irradiance inside a microalgae culture at a depth of z (m) from the

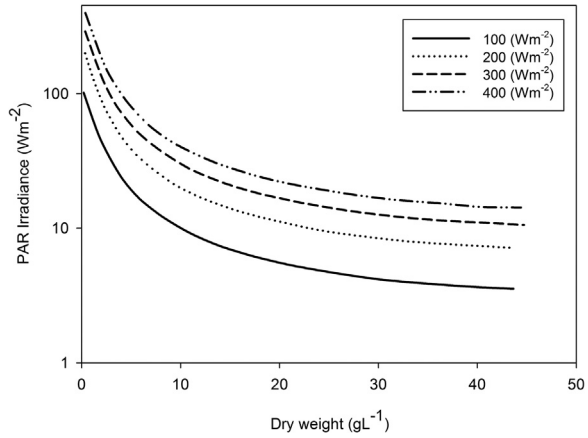

Fig. 6. Dependence of the mean light intensity inside of an 8 mm thick culture layer on Chlorella sp. dry weight.
Reproduced from [1].

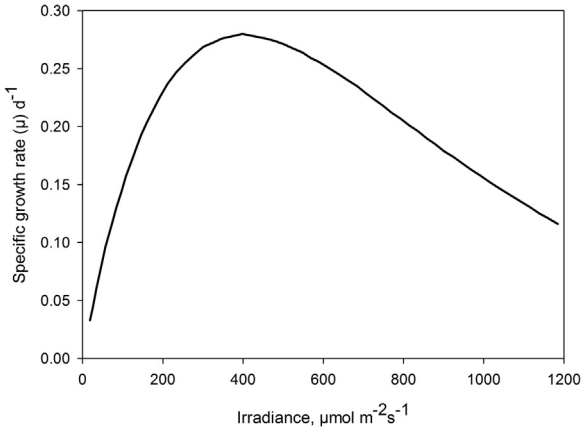

Fig. 7. Curves fitted to experimental specific growth rate versus irradiance for a Chlorella vulgaris/Leptolyngbya sp. co-culture under Steele kinetics.
Reproduced from [29].

culture surface can be estimated by Eq. (2):

$$I = I_0 \exp(-\varepsilon X z), \quad (2)$$

where: I_0 (W m^{-2}) is PAR irradiance, ε (m^2 g dw^{-1}) is the extinction coefficient, X (g m^{-3}) is the biomass concentration [1].

The average light irradiance inside a microalgae culture with a depth of h can be summarized in Eq. (3).

$$I_{mean} = \frac{1}{h}\int_0^h I dz = \frac{I_0 - I_h}{\varepsilon_{mean} X h} \quad (3)$$

where $I_h = I_0 \exp(-\varepsilon_{mean} X h)$ is the amount of light that is not absorbed in the culture depth, and ε_{mean} is the mean extinction coefficient [51]. Doucha and Lívanský [1] used Eq. (3) to measure the relationship between I_h/I_0 inside *Chlorella* sp. culture at different cell concentrations. The following correlation was also found by Doucha and Lívanský [51] for *Chlorella* sp. culture: $\varepsilon_{mean} = \varepsilon_0 (1 - a_1 h/2)(1 - a_2 X)$, with values of empirical coefficients: ε_0 (m^2 g dw^{-1}) = 0.175; a_1 = 46.165; $a_2 = 9.664 \cdot 10^{-6}$. They showed that increasing cell concentration of *Chlorella* sp. leads to decreasing the mean light intensity inside the culture depth (Fig. 6) [1]. It was also shown that *Chlorella* sp. cells absorbed almost all of light incident in the top 6 mm of pond depth when grown at 5 g/L yield of the culture [1].

The biomass production efficiency of microalgae regrading using light energy can be expressed according to Eq. (4):

$$Y_{dw,E} = \frac{P_{dw}}{PFD_d} \times \frac{V}{A} \quad (4)$$

where $Y_{dw,E}$ (g (mol photon)$^{-1}$) is the biomass yield per light energy, P_{dw} (g m^{-3} d^{-1}) is microalgal volumetric productivity of, PFD_d (mol photon m^{-2} d^{-1}) is the total photon flux density, and V/A (m^3 m^{-2}) is the volume to surface ratio of the microalgae culture. The photosynthetic efficiency of a microalgae culture (%) can also be calculated using Eq. (5):

$$PE = Y_{dw,E} \times \frac{C_B}{E} \times 100\% \quad (5)$$

where PE (%) is the photosynthetic efficiency, C_B (kJ g^{-1}) is the microalgal calorific content, and E (kJ (mol photon)$^{-1}$) is the energy input from the conversion of irradiance [29].

Eqs. (4) and (5) shows the dependency of photosynthetic efficiency and biomass productivity on light conversion efficiency. They also indicate that higher light conversion efficiency leads to higher biomass productivity and yield. Furthermore, the relationship of light irradiance and microalgal specific growth rate can be described by the Steele's kinetics model shown in Eq. (6) [61,62]:

$$\mu = \mu_{max} \frac{I_a}{I_{opt}} e^{1 - \frac{I_a}{I_{opt}}} \quad (6)$$

that μ (d^{-1}) is the specific growth rate, I_a (μmol m^{-2} s^{-1}) is the mean irradiance, I_{opt} (μmol m^{-2} s^{-1}) is the optimum irradiance which results in achieving μ_{max}. In this model, the specific growth rate declines when irradiance is increased to a value higher than the optimum irradiance (Fig. 7). The model is appropriate for microalgal cultures with medium density [29]. The optimum irradiance is dependent on species and strain cultivated. For example, *Selenastrum minutum* have the optimum irradiance of 365 μmol m^{-2} s^{-1} [63], *Selenastrum capricornutum* at 391 μmol m^{-2} s^{-1} [64], *Spirulina platensis* at 500 μmol m^{-2} s^{-1} [48], and *Chlorella* sp. at 200 μmol m^{-2} s^{-1} [65].

Many models have been developed for light scattering in a high density microalgal culture, but the most common model for the light attenuation in depth of a concentrated culture is mainly based on the Lambert-Beer law [61]. Light availability to cells reduces in the first couple of centimeters in a concentrated algal culture. In PBRs, there is more homogenous light availability to microalgal cells but photoinhibition is the side effect. The average irradiance in the reactor can be obtained by the following equation:

$$I_a = \frac{1}{d}\int_0^d I(z) dz = \frac{I_0(1 - e^{-k_0 d})}{k_0 d} \quad (7)$$

where: Ia is the average light irradiance received by microalgal cells, d is the reactor depth, z is the aiming depth at which irradiance is calculated, Io is the irradiance at the culture surface, and k_0 is the attenuation coefficient for overall coefficient (from water and biomass):

$$k_0 = k_w + k_b X \quad (8)$$

where: *kw* and k_b are the attenuation coefficient for water and biomass respectively, and X is the biomass concentration (g m^{-3}).

Air, water and the density of culture attenuate the amount of irradiance received by microalgae cells. Microalgae cells can be either photo-limited or photo-inhibited in a culture with no mixing. On the other hand, when there is an appropriate mixing system in culture, microalgae cells are exposed to a cycle of high and low light irradiance and therefore receive similar average irradiance within the cultivation system.

The more homogeneous light distribution can be found in a cultivation system with a shorter light path. However, they are more prone to photoinhibition. On the other hand, the light irradiance regime is more complicated in different parts of the depth but, it is less prone to photoinhibition [29].

3.2. Light and microalgae cultivation systems

Highest areal productivity is the objective of mass microalgal cultivation. Several obstacles and limitations (e.g., mixing, cooling, environmental conditions, etc.) prevent the industrial exploitation of microalgae for mass production of commodity products such as feed, food, and biofuel [34]. Algae must be grown in a container/cultivation center. Open ponds and closed phtobioreactors are two types of cultivation systems, both having advantages and disadvantages. In here, the relative pros and cons of each system when it comes to light and biomass productivity have been addressed. Readers can refer to [14,34,66] for more detailed reviews on algal cultivation systems.

3.2.1. Closed photobioreactors

There are numerous design of closed PBRs including stirred tank [67], vertical tubular [68], bubble column [69], airlift [70], horizontal tubular [71] and, flat panel [72]. Reducing the costs of biomass production is the main goal of any PBR [14]. To achieve that, favoring a sufficient amount of light to the PBR is critical [73]. There are some benchmarks by which a good PBR can be described; a) using light irradiance efficiently; b) having a uniform illumination and reducing mutual shading and c) providing a fast mass transfer of fertilizers, CO_2 and, O_2 [66]. Hence, understanding the effects of environmental parameters such as light on the biomass production within the PBR is required to design an efficient PBR [73,74].

The amount of light irradiance in a PBR increases with increasing culture density. One of the typical solutions for that is to use high light intensity at the PBR surface which leads to photoinhibition. Besides, there is a sharp attenuation of light inside the culture along the light path causing photolimitation. Having a reactor with a high surface to volume (S/V) ratio, therefore, is beneficial to distribute the light more uniformly in the reactor [75]. As a result, there is a more uniform distribution of light into the reactor, more productivity, and more photosynthetic efficiency [58,76]. Jain et al. [75] designed a PBR with integrated waveguides to deliver light evenly across the reactor. The highest volumetric and areal production rate of 22 mg l^{-1} d^{-1} and 2.55 g m^{-2} d^{-1} were attained, respectively at the intensity of 86 μmol m^{-2} s^{-1} [75]. This productivity was two to four times higher than what previously obtained in conventional flat-plate PBR with the light path of 3 cm [77].

Although different closed PBRs have been widely used for microalgae growth and have several advantages such as better control on growth conditions, less contamination to the culture, more light availability for microalgal cells and better mixing rates, there are some significant drawbacks that make PBRs economically and environmentally unfeasible for low cost by-product [73]. The operational cost of PBRs [26] and maintenance issues such as cleaning and sterilization [14], as well as scaling up difficulties [66] are restricting the commercialization of PBRs. Most importantly, the amount of energy that is required for suitable mixing and thus, efficient mass transfer in PBRs such as air-bubbled is more than 100 W m^{-3} (approximately 2000 MJ ha^{-1} day^{-1}) which equals to 50% of the biomass energy content [66].

3.2.2. Open ponds

Open ponds offer a straightforward and profitable approach. Large shallow ponds, circular ponds, tanks, and raceway ponds are the most commonly used open pond systems [9,73]. Raceway ponds are efficient and inexpensive and have been used in the production of algae commercially [14]. Open raceway ponds have been the most common reactors for commercial microalgal production in the last 60 years [78]. A raceway pond has a closed-loop shape with 25–30 cm depth and the surface to volume ratio of up to 10 m^{-1}. This is one of the main disadvantages of open ponds compared with the surface to volume ratio of closed photobioreactors (up to 50 m^{-1} for flat plate PBRs) [79]. The S/V ratio can be increased by decreasing the depth which will improve light penetration but having a large scale raceway pond with the depth of less than 25 cm is not feasible [9,80]. Although easy construction and operation are the main advantages of open ponds compared to closed PBRs, the major constraint is poor light utilization by the cells [5,81]. Additionally, lower biomass productivity and light dilution to the cells stem from insufficient mixing [82].

The light absorption by microalgal cells is affected by various factors such as the cell position, density of the culture and, pigmentation of the cells [30,58]. The irradiance (I_L), at depth (L) of the culture, can be estimated by Eq. (9) [15]:

$$I_L = I_0 e^{-K_a C_x L} \quad (9)$$

where K_a (μE m^{-2} s^{-1}) is the light absorption coefficient which is alga-dependent (can be calculated based on the light-depth profile of an alga at specific cell concentration) and C_x is the biomass concentration. The equation shows that there is a rapid decline in irradiance with increasing depth and biomass concentration as expected [15]. However, to define the precise culture performance of an open pond, the relationship between light received by algal cells and photosynthesis of the culture needs to be understood. For example, light can only penetrate in 5 cm of an algae culture with the density of 0.45 g/L leaving most of the cultures in complete darkness [83].

Various systems have been introduced to overcome the undesirable effects of poor utilization of light or excess of light irradiance in outdoor algal cultures by using of light distribution systems to increase biomass productivity and photosynthetic efficiency [1] which are discussed in the following sections in details.

4. Light distribution systems

4.1. Temporal light dilution (flashing light effect)

Temporal dilution is based on turbulent mixing which results in light/dark frequency and dilution of photosynthetic photon flux density (PPFD) over time. In this phenomenon, microalgal cells are exposed to high light intensity in a short period followed by a longer period in the dark, therefore, decreasing the average intensity below the saturation point. [84]. For the first time, Kok [85] applied rapid mixing method for algae cultures [85]. He observed that when algal cells are provided by high intensity millisecond flashes followed by a long dark period, the energy conversion efficiency is significantly high [85]. This is because only one photon is captured by a photosynthetic unit in a flash of high intensity up to I_{solar}. Thus, the time-averaged light intensity is below I_{sat} [86]. It has been widely argued and investigated that flashing light can effectively increase algal biomass production by a factor of three [87–95]. Optimal flashing light conditions can result in enhancing algal productivity parameters. Moreover, the advantage of using a flashing light system is to have a shorter cooling period over continuous light which will reduce electrical energy consumption and costs [16].

The flashing light is characterized by three main parameters which are the intensity and frequency of light and the light/dark cycle [96]. Consequently, the cycles of mixing can be significantly different and change by order of magnitudes between a millisecond to longer times. Laws et al. [84] designed arrays of foils in 48 m^2 algal culture flume with 4150 L working volume to create systematic mixing. Flowing of water over and under the foils created a pressure differential and thus vortices. Vortices with rotation rates of 0.5–1.0 Hz were produced in a flume having a flow rate of 30 cm/s resulted in an increase in the solar energy conversion efficiencies in the culture of *P. trikornutum* by 2.2–2.4 fold and averaged 3.7% over a three-month period (Table 2) [84]. Besides, Zhang et al. [91] designed a novel raceway pond with a working volume of 412 L equipped with flow deflectors and wing baffles to enhance the effect of flashing light and reduce the dead zone. They found that the pressure loss lowered by 14.58%, fluid velocity increased by 26.89% and dead zone decreased by 60.42%. Moreover, the average L/D cycle also shortened from 14.05 s to 4.42 s, and

Table 2
Summary of different temporal and spatial light dilution systems used for microalgae cultivation systems.

Light dilution system		Reactor	Volume (L)	Species	Produced frequency	Solar energy conversion efficiency enhancement	Biomass enhancement	Photosynthetic efficiency enhancement	Ref
Temporal	Pressure differential	Algal culture flume	4150 L (48 m^2)	*P. trikornutum*	0.5–1.0 Hz	2.2–2.4 fold (3.7%)	–	–	[84]
	Flow deflectors and wing baffles	Open pond	412 L	*Chlorella sp*	Shortened L/D cycle period from 14.05 to 4.2 s	–	30.11% higher productivity	–	[91]
	Flashing light	Flat plate	–	*Scenedesmus dimorphus*	10 Hz	9.6%	2.86 times higher productivity	–	[49]
Spatial	Cones	Open pond	2000 L	*Chlorella*	–	–	27 g l^{-1} to 38 g l^{-1}	–	[101]
	Fresnel lenses	Spatially diluted PBR	18 L	*Neochloris oleoabundans*	–	–	2.5 time higher productivity	–	[103]
	Optical fiber	Bubble column	2.5 L	*Synechococcus* sp.	–	–	4.2 times higher productivity	–	[105]
		Airlift	130 L	*Spirulina platensis*	10 Hz	–	43% higher productivity	–	[18]
		Airlift	130 L	*Scenedesmus dimorphus*	10 Hz	–	38% higher productivity	–	[18]
	PMM[a] tubes	Flat plate	3.3	*Chlorella vulgaris*	–	2–6.5 times higher average light intensity	23.42%	12.52%	[72]
	Fluorescent dyes	Flat plate	270 ml	*Chlorella sp*	–	–	10% higher productivity	Higher Chl *a* content from 27^a10^6cellml^{-1} to 48^a10^6cellml^{-1}	[117]
	Luminescent solar concentrator panels	Flask	250 ml	*Chlorella vulgaris*	–	–	Higher growth rate($\mu = 0.29$ compared to $\mu = 0.23$)	Lower doubling time (td = 2.44 d compared to td = 2.98 d)	[118]
		Open pond	50 L	*D. salina*	–	–	–	Higher Chl *a* content	[118]
		Luminescent acrylic PBR	450 ml	*Chlorella vulgaris*	–	–	Higher biomass concentration and biomass productivity (max = 1.49 g l^{-1} and 0.135 g l^{-1} d)	–	[100]
		Luminescent acrylic PBR	450 ml	*Gloeothece membranacea*	–	–	Higher biomass concentration and biomass productivity(max = 2.27/l and 0.132 g l^{-1} d)	–	[100]
		Open pond	–	–	–	–	230% increase (2445^a10^4 cells/ml compared to 1000^a10^4 cells/ml)	–	[119]

[a] Polymethyl metacrylate.

significant swirling flow was produced. They proved that *Chlorella* sp. had 30.11% more biomass productivity when cultured in a raceway open pond with wing baffles compared to the control pond in outdoor cultivation (Table 2) [91]. Lunka and Bayless [49] also used flashing light on *Scenedesmus dimorphus* culture in a thin flat-plate bioreactor. A constant photon flux of 75 μmol photons m^{-2} s^{-1} and three flashing light intensities of 375, 275, and 175 μmol photons m^{-2} s^{-1} were used. They found that the lowest energy consumption (9.6% less power) and the highest biomass productivity (2.86 times higher productivity) were achieved when the photon flux of 375 μmol photons m^{-2} s^{-1} was used (Table 2) [49].

Overall, a flashing light system is effective in a microalgae open pond cultivation system as long as the mixing velocity is optimized in the culture. That means that the microalgae culture should be harvested and diluted over the time to keep the cell density at an optimum concentration [16]. However, conventional mixing systems in outdoor open ponds do not effectively enhance the conversion efficiency of light by flashing light effect. To achieve an optimum L/D cycle with the timescale of the flashing light, a sophisticated mixing system is required for an algal cultivation system which is technically not feasible and may induce high operational costs [26].

4.2. Spatial light dilution

Spatial light dilution is a method to decrease photon flux density lower than 10% of full sunlight by using light distribution systems [25,97]. One potential advantage of spatial dilution compared to the flashing light system is that the conventional mixing can be used. It seems that temporal light dilution requires simpler optical system and fewer capital costs than spatial dilution but the operational costs may be considerably higher due to having a turbulent mixing facility to induce high frequency light/dark cycle [86]. Obtaining the irradiance below the saturation intensity by applying spatial dilution systems requires optical concentrators and diffusers such as optical fibers [18], trough systems [98], parabolic dishes [74], green solar collector [99] and, luminescent solar concentrator panels [100].

Mayer et al. [101] cultivated a 2000 L mass culture of *Chlorella* in an open pond with 1 m depth. They could increase the biomass productivity of the culture from 27 g d^{-1} to 38 g d^{-1} by using translucent perspex cones as a light diffusing system into the open pond culture (Table 2) [101]. The similar study was carried out by Badby [102] to investigate the effect of diffusers to increase light irradiance into the pond and enhance microalgal productivity. The diffusers increased the amount of light supplied to a concentrated culture up to 20% but did not increase areal productivity. The possible reasons were likely due to carbon limitation and oxygen saturation within the algal culture [102]. Furthermore, Dye et al. [103] designed a diluted photobioreactor (sdPBR) cultivation system with 18 L to concentrate and distribute light over the larger area. They used Fresnel lenses as the solar concentrators, and the planar waveguides to transfer the light into the photobioreactor which resulted in a 2.5 times higher productivity (Table 2) compared to conventional systems.

4.2.1. Optical fibers

Using fiber optics is another method to carry light to the PBR [104]. The use of fiber optics systems for microalgal photobioreactors can potentially address two important criteria in the design of a lighting system for algal photobioreactors: (a) electrical energy efficiency; and (b) lighting distribution efficiency [83]. Takano et al. [105] investigated the construction of 661 light diffuser optical fiber (LDOF) bundles in the middle of a bubble column PBR with 2.5 L working volume for *Synechococcus* sp. culture. They found that increasing light intensity from 2.5 μmol m^{-2} s^{-1} to 20 μmol m^{-2} s^{-1} using LDOF will increase biomass yield by 4.2 fold to the total yield of 0.97 g/L (Table 2) [105]. Xue et al. [18] also designed an airlift PBR with 130 L working volume by using optical fibers which were fixed vertically inside the reactor. They showed an increase of 43% and 38% in productivity for *Spirulina platensis* and *Scenedesmus dimorphus,* respectively, as a result of having an even distribution of light/dark frequencies being over 10 Hz (Table 2) [18]. Although optical fibers can be made in different designs and they are separate from the reactor resulting significantly higher productivity [83,106], delivering light into mass cultivation of algae through optical fibers can be very inefficient [107]. It has also been argued that fiber prices are exceedingly high around tens of (US) dollars per linear meter suggesting the use of fiber optics as the economic bottleneck in such systems [97]. Besides, other issues such as high installation and maintenance fees and high capital costs make the use of optical fibers unachievable in a large scale cultivation system [107].

Sun et al. [72] designed a 3.3 L flat-plate PBR equipped with polymethyl methacrylate (PMMA) tubes inside the reactor as light guides for *Chlorella vulgaris* cultivation. The average light intensity and biomass production were increased by 2–6.5 times and 23.42%, respectively (Table 2). The photosynthetic efficiency of *Chlorella vulgaris* was also increased to 12.52% [72]. The other spatial light distribution method is the potential use of green solar collector (GSC) modeled and designed by Zijffers et al. [99] to collect the sunlight and deliver it into the photobioreactor via flat rectangular PMMA. The design is based on the capture of sunlight by Fresnel lenses on top of the GSC that can rotate to follow the sun and is directed to the photobioreactor through light guides. Their design showed a better efficiency compared to previous attempts to capture sunlight through optical fibers. The GSC system has several advantages compared to optical fibers including no loss of light in transport into the system and lowers costs and construction consideration for large scale systems due to using ease of construction and maintenance and the use of cheap material (PMMA). However, setting up the tracking sun system and positioning the lenses are the major drawback of the system which makes this system economically unfeasible. Furthermore, incident angles of sunlight vary greatly during a day and, therefore, a uniform distribution of light on the surface of the distributor is not achievable [17].

4.2.2. Luminescent solar concentrator

Luminescent solar concentrators (LSCs) for concentrating and converting sunlight into electricity through photovoltaic cells have been first reported by Weber and Lambe [108]. The advantage of LSCs is that there is no need for an expensive solar tracking system as LSCs can absorb direct and diffuse light [109]. LSCs consist of luminescent particles such as organic dyes [110], quantum dots (QDs) [111], or semiconducting polymers dispersed uniformly inside it [112] (Fig. 8). The sunlight is absorbed by the surface of a luminescent panel through luminescent dyes. The absorbed light undergoes total internal reflection towards the edges and is emitted at a longer wavelength [110,113].

Using LSCs for microalgae cultivation systems have been reported in the literature [100,114–116]. Delavari et al. [117] investigated the effect of fluorescent material coated on a 270 ml flask to enhance the growth rate *Chlorella sp*. The two absorption and emission peaks of the coated layer were at 370–380 nm and 435–465 nm, respectively. They showed that the biomass productivity of *Chlorella* sp. increased 10% by using coated reactors with shifter layers compared to control. It was also found that chlorophyll *a* content increased from 27×10^6 cell ml^{-1} to 48×10^6 cell ml^{-1} due to removing UV-A radiation [117].

A similar study was carried out by Detweiler et al. [118] cultivating four strains of microalgae as *Chlorella vulgaris, D. salina, Chlamydomonas reinhardtii, Botryococcus sudeticus* and a cyanobacteria (*Spirulina platensis*) in a 250 ml flask with 100 ml working volume under greenhouse building covered by LSCs panel. They used red LSC panels that had an absorption peak at 400 nm and emission spectra at 600–700 nm range. The results showed that growth rate increased and doubling time decreased significantly for *C. vulgaris* under the red LSC panel ($\mu = 0.29\ d^{-1}$; $t_d = 2.44$ d) compared to the control reactor ($\mu = 0.23\ d^{-1}$; $t_d = 2.98$ d) (Table 2) [118].

Mohsenpour and Willoughby [19] also cultivated *Chlorella vulgaris*

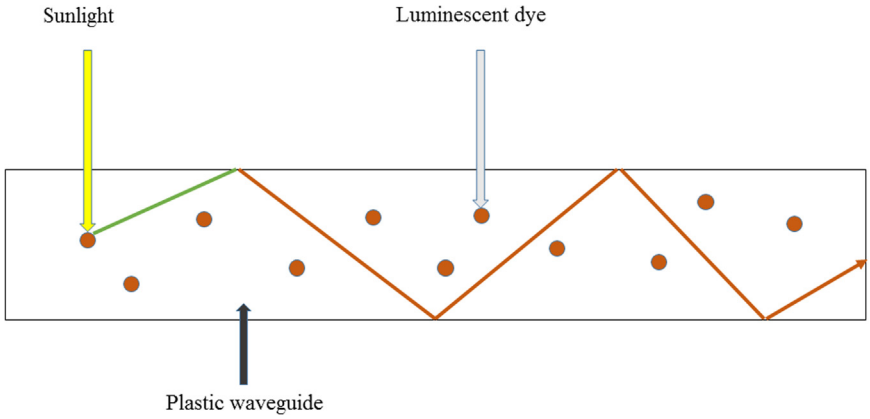

Fig. 8. The luminescent solar concentrator. Incident light (yellow arrow) is absorbed by luminescent dyes (red circles) inside the waveguide and re-emitted at longer wavelength to the edge(s) by total reflection [109]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

and *Gloeothece membranacea* in bubble column PBRs coated with luminescent filters in blue, green, yellow, orange and red with working volume of 450 ml at different initial culture densities (Table 2). The results indicated that the biomass productivity increased in red luminescent PBRs by 1.14 and 1.62 times in *C. vulgaris* (0.135 $g\,l^{-1}\,d^{-1}$) and *G. membranacea* (0.184 $g\,l^{-1}\,d^{-1}$) cultures, respectively. The chlorophyll production increased in *C. vulgaris* by green light; however, light conditions did not affect chlorophyll production in *G. membranacea* cultures. The highest chlorophyll content of 1.98% of biomass was produced by *C. vulgaris* under green light compared to 1.14% for control which shows the effect of green light on pigmentation [19].

A large scale open pond study using LSCs was reported by Falber [119] who invented a bioreactor comprised of luminescent solar concentrator panels with triangular shaped bags. The algae were grown inside the LSCs panel while the inverted triangular spaces between panels were filled with water to be used as a light path. Additionally, the water was considered as a thermostat. In the summer, the water may be released and replaced by clear water and the heat will take away from the system and in the winter, the water can keep the temperature of the algae at the level required for algae. By using this system in an open pond with LSCs panel, he produced 230% more algae biomass compared to the control system without luminescent panels (approximately $2445 * 10^4$ cells $ml^{-1}\,d^{-1}$ compared to $1000 * 10^4$ cells $ml^{-1}\,d^{-1}$) (Table 2) [119]. This system showed a significant increase in biomass concentration, however, it requires a huge amount of water.

On the other hand, Miglio and Palmery [120] used a flat plate PBR with 750 ml volume made of a red luminescent solar concentrator and resulted in no significant difference in specific growth rate and photosynthetic efficiency of *Nannochlropsis* culture [120].

Overall, spatial light dilution systems seem to be a better and cheaper option than temporal light dilution due to better efficiency in microalgal growth. Among all spatial light dilution systems, LSC panels appear to be a suitable method to be used in microalgal culture systems to have a better efficiency. The advantages of LSC panels are easy to construct, cost-effectiveness, no need for a sun tracking system, feasibility to be used in outdoor open pond systems and, the ability to produce electricity. However, any diffusers design will need to be easily scalable to a commercial scale. Fouling and durability issues of diffusers will also need to be tested at the scale. Due to the wide range of other factors and limitations constantly interacting with an outdoor algal culture, it is likely that much more research is needed to determine the light diffusers true value to different commercial cultivation species.

5. Techno-economical and policy analysis

5.1. Techno-economical analysis

Microalgal large-scale cultivation started with *Chlorella* in Japan and Taiwan in the 1960s and continued with *Spirulina* (in 1960s) and *Dunaliella* (in 1970s). Nowadays, these large-scale ponds are spread all around the world [9121] with the largest plant based in Hutt lagoon in Western Australia (700 ha un-mixed pond) [9]. There are two major algal cultivation systems, open ponds and closed photobioreactors (PBRs). Cultivation of microalgae in closed PBRs results in high biomass productivity [34] and low contamination risks but very high Capex and Opex. Open ponds such as paddle wheel driven raceway ponds are less expensive, but have a lower biomass productivity (maximum average annual = 20 $g\,m^{-2}\,d^{-1}$) [9]. Raceway ponds are the preferred commercial microalgal cultivation system for production of *Arthrospira*, *Chlorella, Haematococcus,* and *Dunaliella* [122]. The estimated cost of algal biomass achieved in large scale raceway ponds and PBRs for different species are summarized in Table 3 [123]. The main advantages of using raceway open ponds for microalgal mass cultivation are a) no need for a cooling system, b) lower hydrodynamic stress and, c) lower capital and operational costs [66].

Economic is the main challenge of cultivating microalgae in large scale raceway ponds for biofuels production. To have economically feasible biofuel from microalgae, there needs to be a sharp reduction in production costs [133]. One potential way to the overall cost of biomass by an order of magnitude is to increase biomass productivity as it would significantly affect the economies of a large scale microalgal production [122]. Capital and operational costs of microalgal growth in raceway ponds with 30 and 60 $g\,m^{-2}\,d^{-1}$ productivities are summarized in Table 4 [133] and the estimated cost of microalgal oil has been calculated between $51 and $90 per barrel [134] for two different yields and CO_2 supply methods (Table 4). It is to be noted that, so far the highest achieved microalgal annual average biomass productivity has been reported to be only 20 $g\,m^{-2}\,d^{-1}$ [9]. Although the productivities reported in Table 4 could theoretically be possible, such a high yield has to be obtained in practice consistently [9,133].

Carriquiry, Du [133], also has estimated the impacts of biomass productivity on production cost of biofuel from microalgae (Fig. 9). The importance of high microalgal productivity on reducing production costs as well as improving oil yields is also summarised in Fig. 9. Such a theoretical value would certainly result in producing economically sustainable algal biofuel at less than USD 0.7 (Fig. 9).

The maximum biomass productivities reported in Table 4 are based on the photosynthetic conversion efficiency of 10% of solar energy [134] while the achievable photosynthetic efficiency in microalgae is 2–3% in practice [26]. As discussed previously, one solution to increase microalgal productivity is to use an appropriate light delivering system. Such a method can significantly increase the availability of light to algal cells hence increase photosynthetic efficiency. In other words, a better light delivery system into the microalgae cells can increase algal biomass productivity. It is to be noted that such a method would certainly increase the capital expenses of the process but if the productivity is increased significantly, such a method would result in reducing the overall production cost and for the same amount of product less number

Table 3
Cost estimation of algal biomass grown in raceway ponds from different studies (All costs are adjusted to 2018 US inflation rate) (Reproduced from [123].

Algae species	Culture system	Culture area/ volume	Productivity (g m^{-2} day^{-1})	Estimated Cost ($US kg^{-1})	References
Scenedesmus	Raceway	4 ha	20	7.56	[124][a]
Chlorella (Photoautotrophic)	Raceway	10	25–30	12.42	[125][b]
Chlorella (Mixotrophic)	Raceway	10 ha	25–30	12.64	[125][c]
Spirulina	Raceway	2 ha	12	12.57	[126]
Porphyridium	Tubular PBR	10 ha	16	10.21	[127]
Spirulina	Raceway	5 ha	3.2	20.20	[128]
Dunaliella salina	Raceway	2 ha	4	12.75	[129]
Chlorella	Thin-layer Cascade	1 ha	18	23.71	Data from Pilot-scale facility at Dongara, Western Australia[d]
Microalgae	Tank Culture	20,000 L	–	79.57	[130]
Microalgae	Biocoil	2400 L	0.06 g/L d^{-1}	27.50	Unpublished Data[e]
Spirulina	Raceway	1.5 ha	15	13.35	[131][f]
Nannochloropsis	Raceway	0.2 ha	16 (summer), 8 (winter)	54.99	[132][g]

[a] Based on experience of Indo-German project in Mysore, India.
[b] Freeze-dried.
[c] Spray-dried.
[d] Includes harvesting and spray-drying costs – no depreciation of capital costs.
[e] Does not include harvesting and drying costs – no depreciation of capital costs.
[f] Grown on sago starch factory wastewater.
[g] Only biomass production cost. Harvesting costs etc. not included.

of ponds would be required. Furthermore, there is also a chance of reducing energy cost by co-producing electricity using light delivering systems such as luminescent solar concentrator panels [12]. The potential advantage of using luminescent solar concentrator panels for microalgae production is the production of electricity using photovoltaic cells as well as delivering the light into the microalgae culture and thus, reducing the cost of energy and biomass production.

5.2. Policy constraints

There is no doubt that worldwide the policies of using energy is encouraging utilization of renewable energy [133]. The US Energy Independence and Security Act (EISA) of 2007 specify a production of advanced biofuel at 79.5 billion liters by 2022 as a part of second Renewable Fuel Standard (RFS2) [133]. The main challenge of producing microalgal biofuel is economics. When using conventional growth systems such as raceway ponds, cost of microalgal biofuel production is too high compared to fossil fuel [133]. Increasing biomass productivity in large scale cultivation systems is a promising way to lower the biofuel production. The application of using luminescent solar concentrator panels in microalgae cultivations is in early stage specifically in outdoor cultures. There is a very limited study on using LSCs in outdoor microalgae cultures which makes the economic assessment of this method very difficult. Another obstacle for using LSCs for algae raceway ponds is the design of the panels. Design of the luminescent panels can have a significant effect on biomass productivity of outdoor

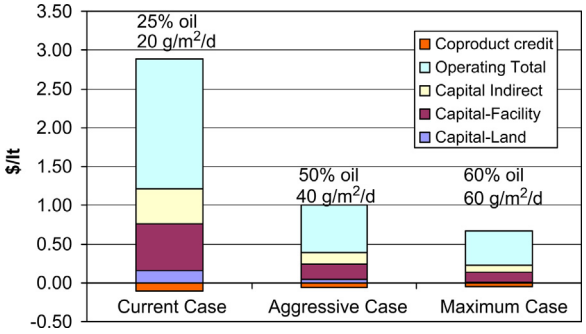

Fig. 9. Effect of productivity on costs of oil production. (Copied from [133].with permission).

ponds which affects the capital costs accordingly. Furthermore, there should be an exclusive study of using luminescent panels on specific algae species in an outdoor pond to be able to find the suitability and true potential of the panels for the outdoor algal cultures. Therefore, we need more investigations on using luminescent solar concentrator systems in algal ponds in terms of application and economics.

5.3. Future perspective

As highlighted earlier, light is the main limits to the growth and productivity of algae. There is no doubt that distributing light more

Table 4
Capital and operating costs for a microalgae open pond system with two different biomass productivity. (All costs are adjusted to 2018 US inflation).
Source: Reproduced from [133].

	30 g m^{-2}/d 109 tonnes/ha/yr		60 g m^{-2}/d 218 tonnes/ha/yr	
	Remotely supplied CO_2	On-site flue gas	Remotely supplied CO_2	On-site flue gas
Capital costs ($)	113,446	106,561	159,727	143,816
$/tonne-yr biomass	1040	979	734	658
Operating costs($)[a]	23,210	16,631	25,504	23,362
Capital charge (15%)	16,982	16,064	23,944	21,573
Total annual costs ($)	40,192	32,695	49,448	44,935
$/tonne biomass	369	300	226	206
$/barrel of algal oil	105	86	64	60
$/L of algal oil	0.67	0.54	0.40	0.37

[a] Labor and overhead would amount to about $4590 and $6119 for the low and high productivity cases respectively.

evenly and increasing light availability to algal cells will enhance the biomass productivity and photosynthetic efficiency in outdoor raceway ponds. Among spatial light dilution systems, LSCs seem to be one of the most economical and effective systems to be applied in raceway open ponds. LSCs can be solving the poor light availability issue of algal cells in raceway open ponds. However, it should be noted that the technology of using LSCs for algal cultivation is still at very early stages and needs further investigation for finding the potential of this technology in commercial scale microalgal cultivation.

6. Conclusion

It has been argued that microalgae culture is yet unable to supply basic human needs that stem from the incapability of utilizing solar energy efficiently [135,136]. Photolimitation, photosaturation and, photoinhibition are crucial factors which may happen during a growth of concentrated microalgae cultures specifically those being cultivated outdoor under sunlight. By using filtering and light dilution systems, the photoinhibition and photolimitation can be reduced. This leads to a higher productivity culture. There are mainly two dilution systems, temporal and spatial, for distributing light into the microalgae culture. Among spatial dilution systems, LSCs seems to have a good potential to be used in commercial microalgae cultivation systems. They potentially combine spectrum shifting properties with spatial dilution to channel the light into the culture where it is needed. However, only a limited number of studies have been done on LSC for microalgae cultivation, and further studies need to be carried out to find out the true potential of LSC panels.

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