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Review

Design principles of photo-bioreactors for cultivation of microalgae

The present hype in microalgae biotechnology has shown that the topic of photobioreactors has to be revisited with respect to availability in really large scale measured in hectars footprint area, minimization of cost, auxiliary energy demand as well as maintenance and life span. This review gives an overview about present designs and the basic limiting factors which include light distribution to avoid saturation kinetics, mixing along the light gradient to make use of light/dark cycles, aeration and mass transfer along the vertical or horizontal main axis for carbon dioxide supply and oxygen removal and last but not least the energy demand necessary to fulfil these tasks. To make comparison of the performance of different designs easier, a commented list of performance parameters is given. Based on these critical points recent developments in the areas of membranes for gas transfer and optical structures for light transfer are discussed. The fundamental starting point for the optimization of photo-bioprocesses is a detailed understanding of the interaction between the bioreactor in terms of mass and light transfer as well as the microalgae physiology in terms of light and carbon uptake kinetics and dynamics.

Keywords: Light transfer / Mass transfer / Photo-bioreactor

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1 Introduction

Production of microalgae biomass is up to now limited to a few thousand tons per year, mostly produced in open ponds. Only a few hundred tons are produced in closed photo-bioreactors. In the last years algal biomass has found an overwhelming interest for low value biofuel production. Therefore, the production has to be increased by several orders of magnitude. The advantages of photo-bioreactors in this process are quite clear: they offer cultivation under a wide variety of conditions or prevent to some extent outcompeting of the production strain by other algae or contamination with undesirable microorganism or grassers. The main benefits of closed bioreactor systems include higher areal productivities and the prevention of water loss by evaporation. Since Borowitzka [1] published an assessment, closed photo-bioreactors have undergone continual development through a process driven by experience but also by targeted engineering. Some of the points mentioned such as high costs are still critical issues. Other reviews [2–5] mark the beginning of a new awakening in rational photobioreactor design. Basic process engineering principles regarding light distribution, mass transfer, and hydrodynamics have been set up e.g. by Janssen [6], which are nowadays still under consideration. This process did not converge yet as was the case with the heterotrophic stirred tank reactors. Different geometries and operating methods developed depend on the local conditions, the product to be produced, and economic constraints. Indeed, commercially available closed photobioreactors still do not represent an optimal solution in many different regards. Even if areal and volumetric productivity is higher than in open ponds, the performance does not come close to theoretical maxima and can not even reach values obtained at lab scale. Besides, the lack of performance, investment, and operation costs are still estimated as being far too high. In order to guarantee an economic design for production of energy products, investment costs may not exceed 40 €/m^2 [7], as a very rough estimate, while available reactors still cost several times this value. In nearly all the cases of real photo-bioreactors investigated, the auxiliary power required is also too high, while the obtained biomass concentrations are too low. However, there has been significant progress in the last years. This review will announce basic trends emerging from research to enhance bioreactor performance and reduce capital costs. In addition a cautious outlook will give reference to future options.

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2 Definitions and performance evaluation of closed photo-bioreactors

Although there is only a limited number of algae production plants in operation employing closed reactors, a direct evaluation is hardly possible. One problem in comparing different designs of photo-bioreactors is the use of different measures depending on the purpose of a reactor and even depending on the research discipline. Fig. 1 shows a schematic diagram of parameters important for bioreactor design.

V_R [L] The total working volume of the reactor includes liquid and gas phase; the volumes of the pure liquid are usually not given as would be necessary for mass balancing.

A_R [m^2] or [ha] The total surface area of the transparent part of the reactor determines the amount of light which could eventually enter the reactor; detailed analysis is necessary, to calculate how much light can really hit the surface. The surface area makes a serious contribution to reactor cost.

A_G [m^2] The aperture (ground) area of the reactor measures the area from which light energy is collected. For multiple installations the area between two reactors has to be included on a pro rata basis in the areal calculation to facilitate accurate scale. This can give cause for concern in cases of single but high fences which have a small footprint but nevertheless large tailed area. To distinguish clearly between the footprint of a single reactor and the area requirements of an arrangement of reactors including space between them, the term "overall areal productivity" (OAP) has been introduced [8].

P_R [$g\,L^{-1}\,d^{-1}$] The volumetric productivity $P_R = dm_X/(V_R \cdot dt_C)$ measures the product formation per reactor volume and time span. Lab scale experiments are often given on this volumetric basis. This is an important value for high value applications like production of pharmaceuticals and for assessment of process intensification. Volume contributes to the overall cost.

P_G [$g\,m^{-2}\,d^{-1}$] = [$3.65\,t\,ha^{-1}\,a^{-1}$] The areal productivity $P_G = dm_X/(A_G \cdot dt_C)$ is the most important parameter to assess larger photo-bioreactor plants. It allows for balancing in terms of energy efficiency between incident light as the main energy source and biomass or product formation on an areal basis and is the determining performance criterion. This is especially true for conversion of solar energy to chemical energy e.g. biodiesel produced by microalgae. Although the areal productivity is quite informative for comparison of designs, the value depends to a great extent on the irradiation during the measurement period.

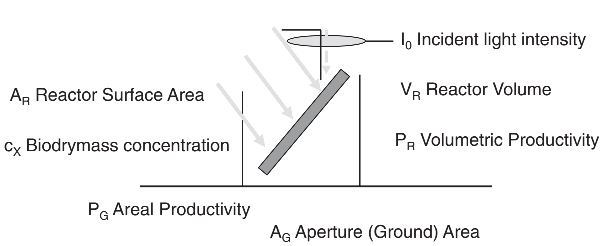

Figure 1. Bioreactor design parameters, definitions and items for assessment.

I_0 The irradiance (at the surface) is given as photon flux density PFD [$\mu E/(m^2\,s)$], where E [Einstein] stands for mol photons. PPFD is the photosynthetic photon flux density. This unit accounts for the fact that photons can only be used from the photosynthetic active radiation range (PAR 400 nm–700 nm). For the calculation of large areas e.g. for feasibility studies of bio-energy production, the irradiance is given as power density in [W/m^2]. Specification whether it is for PAR or the whole solar spectrum including UV and IR should be given. While for macroscopic considerations the radiation is measured in normal direction to earth, for kinetic studies it is measured in normal direction to reactor surface. The index 0 stands for the value at the surface.

PCE The photoconversion efficiency measures the fraction of the solar energy that is converted to chemical energy in a photo-bioprocess. The maximum theoretical value has been estimated to be 9% [74, Tredici, International Algae Congress, Amsterdam, 2008] for full sunlight. Practically achieved values for PCE_{Par} are in the range of 10% for PAR or PCE_{Sol} of 5% for the full sunlight spectrum. For the calculation of PCE the energy content of the biomass has to be measured. It can range from 20 MJ/kg to 30 MJ/kg for oil rich algae. According to thermodynamics oil rich algae could show lower areal biomass productivities than other algae, cited from [9], but this can nevertheless mean a high PCE, which is at the end the decisive value. PE is used for the photosynthetic efficiency.

3 Interactions between physiology and reactor design

A typical photo-bioreactor is a three phase system, namely the liquid phase which is the medium, the cells as the solid phase, and a gas phase. Light which is the unique feature of photo-reactors is a superimposed radiation field, sometimes but not uniquely called a fourth phase. The design of an adapted PBR requires understanding of the interaction between the environmental parameters and the biological response. The main interactions are indicated in Fig. 2. Some of these interactions and their role in reactor design will be outlined in this section as different aspects.

Aspect 1: Light saturation and light dilution

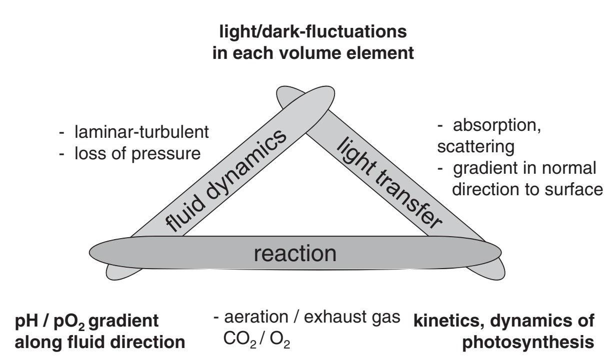

Figure 2. Interactions between fluid dynamics, biochemical reaction, and light transfer in photo-bioreactors; the specific characteristics of the phases and their interactions mark the principal problems to be considered in reactor design.

With respect to light the more the better is not true for microalgae. Most of them are adapted to low light intensities representing only a fraction of the full day light even in mid-latitude regions. A typical example of growth kinetics here for *Porphyridium purpureum* is given in Fig. 3 [10]. While this growth kinetics is measured for fully adapted continuous cultures (photoacclimatization), similar curves e.g. for *Chlamydomonas* have been described for short time experiments resulting in the so called PI-curve [11]. After a linear increase of growth rate with increasing light intensity (Blackman kinetics) saturation is approached in the example given here at about $100\,\mu E/(m^2\,s)$. This is only 10% of the midday sunlight intensity in a European summer. Light in excess is wasted as fluorescence and finally heat [12].

The answer of process engineering is to design vertically mounted photo-bioreactors with a large surface area. These could be flat panels or alveolar panels. The sunlight, falling on a given ground area, is spread over a larger reactor surface area. As a result, the microalgae are irradiated with only a small fraction of the whole intensity of the incident radiation and grow in the non-limited region of the light saturation curve as indicated in Fig. 3. That means that the surface to ground area ratio A_R/A_G should be in the range of 10 or higher. The optimum value depends on the strain and the region, where the reactor is in operation. Nevertheless, this is on the cost of requiring more reactor construction material and more volume. To allow the light to reach the transparent surfaces and its dilution in a horizontal direction especially at day times with high radiation, the fences (Fig. 4) are usually mounted in north/south direction.

Some authors [13, 14] propose stacks of plates alliance perpendicular to the angle of incident light. This design has been used in order not to achieve light distribution in the sense of aspect 1, as is sometimes assumed mistakenly, but to establish compartments with high and low light conditions. This can be useful for algae with different photo-acclimatization conditions or formation of specific products which are produced only under strong light conditions.

Aspect 2: Light attenuation and light path length reduction

The spatial distribution of the light intensity inside the reactor is, apart from the geometry, mainly influenced by light attenuation caused by mutual shading of the cells via adsorption by the pigments or via scattering by the cells. Some mechanistic formulae for calculating light gradients in liquid particle systems have been published, however, for a small and flat volume element an exponential development depending on biomass concentration can be assumed [15]. As long as the light path length exceeds the plate thickness, more or less exponential growth can be observed. For *Porphyridium* e.g. the light path length is 20 mm for $c_X = 2.0$ g/L. After the biomass concentration reaches higher values, there will be only linear growth. That does not mean that the process is automatically less efficient. As long as proper mixing and light distribution is achieved, the linear increase in biomass is proportional to incident light. However, a fraction of the total volume is dark. It therefore does not contribute to productivity but to energy cost. In addition, high concentrations can be reached faster with a lower dark volume fraction. Assuming that a given fraction of the incident light is converted to cell mass (usually photon conversion efficiency $PCE_{Sol} < 5\%$ full spectrum [16]), then the produced cell mass is diluted in a smaller volume in case of thin film reactor leading faster to high cell densities. Of course, medium composition has to be adjusted to these high concentrations. High cell densities, e.g. $c_X > 10$ g/L, have big advantages in saving energy for mixing and during downstream processing. To achieve high cell densities the reactor thickness should be as small as possible. Richmond [17] already focussed on that point arguing that the short dark/light cycles (see aspect 3) is a crucial point to obtain such high cell densities.

The two aspects given above can be summarized by the requirements for a high surface/volume ratio (SVR) [18]. Most current reactor designs follow this principle. The three most important geometries are given in Fig. 6. Installing many plates quite close together increases both SVR and the areal water coverage, defined here as the total fluid volume per ground area. To bring more surface area to a given ground area should be carefully counterbalanced with reducing volume per ground area on the basis of the kinetics to provide not more light distribution than necessary and to save volume for high biomass concentration and reduced energy.

Aspect 3: Light fluctuation and mixing

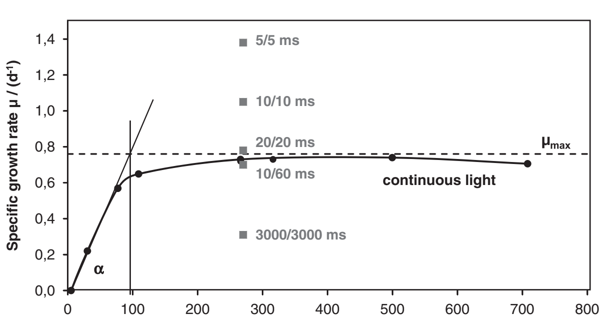

Figure 3. Growth kinetics of *Porphyridium purpureum* [10]; the solid line and the related symbols represent specific growth rates from continuous cultivations with continuous light, the single symbols represent growth rates for different patterns of light/dark-cycles.

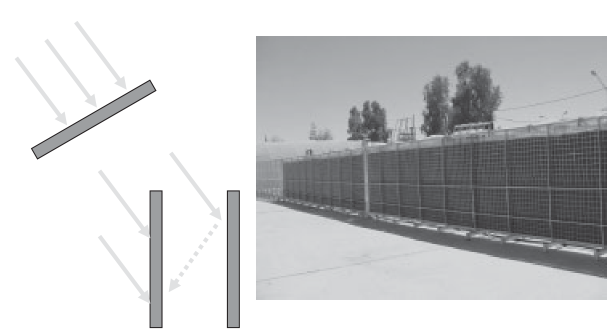

Figure 4. Principal of light distribution over a vertical surface; the picture shows a "green wall panel" (GWP) [76] installation of the University of Almeria, with kind permission of E. Molina Grima. He reported 2008 the following data: $V_R = 5.0\,m^3$ per unit, $P_V = 0.6$ g/L/d, cost 3000 €/m^3.

Local turbulences carry the cells more or less randomly through well-illuminated volume elements near the glass wall and poorly illuminated reactor zones remote from light incidence, so each individual cell is exposed to statistical dark/light cycles. These cycles have a strong effect on algae growth. Several authors observed dependency of growth from mixing time constants in lab scale experiments. These studies demonstrated [19] that the benefits of mixing were not only due to mass transfer, but also the increased frequency of the light/dark cycles [20]. In ideally illuminated lab-scale modelling reactors, Fig. 5, light cycles and mixing can be decoupled at least for low or moderate biomass concentrations. While mixing is provided with an agitator as usual, illumination and light/dark cycles are induced by artificial illumination via LEDs [21]. Data out of such experiments under continuous cultivation are shown in Fig. 3. Cycles below 0.3 Hz lead to low growth rates even lower than expected from the light times alone. Coupling of these cycles with intracellular control loops on the epigenetic level is discussed for explanation. So persistent light/dark-cycles which means mixing time constants below 1 Hz should be avoided [22, 23] and this is not easy in large scale reactors and may be the reason for low yields of some large reactors. For very fast cycles in the range of kHz light energy stored in the photo-systems during passage through bright zones of the reactor can be used further in metabolism during the passage through the dark zones. This so-called "flashing light effect" has been frequently investigated e.g. [24], nevertheless the occurrence assuming this strict definition (in contrast to slower cycles caused by Rubisco limitation) has not been unequivocally proven yet in pilot/production scale. Nevertheless, also cycles between 1 Hz and 1 kHz are very useful. The transition between slow cycles, where no storage effects occur and fast cycles with nearly complete integration has been described in [25]. Such fast mixing is accompanied by a high waste of mechanical energy and is therefore only likely to become a viable option in future reactor generations.

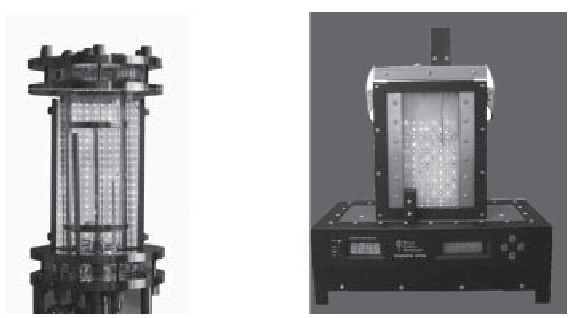

Figure 5. Model reactors for measurement of kinetics and dynamics. Light is homogeneously distributed either by using the lense effect or by using thin plates. LEDs allow for application of fast light/dark cycles up to 1 kHz with high intensities.

Aspect 4: CO_2-supply and aeration

Beside light transfer the most important task of photobioreactors is to feed the algal cells with carbon dioxide for photosynthesis and to remove the produced oxygen from the medium. The CO_2-demand of the culture can be calculated on a stoichiometric basis by the carbon content of the biomass. The carbon fraction varies from 0.45 for algae with high carbohydrate content up to 0.8 for oil rich cells. Accordingly, the stoichiometric CO_2 requirement of the algae lies at 1.85 g CO_2/g biomass or higher. Assuming for example a growth rate of $\mu = 1\, g/(g \cdot d)$ at a biomass concentration of 1 g/L the necessary carbon dioxide transfer rate (CTR) would be $1.85\, g/(L \cdot d)$. This amount of carbon dioxide has to be fed constantly to the reactor and this is usually achieved by bubbling with CO_2-enriched gas bubbles. In this example using 10 vol. % CO_2 in the gas the CTR corresponds to a minimum aeration rate of 0.006 v/v/min. Also pure CO_2 is occasionally applied. A second constraint concerns the carbon dioxide uptake kinetics. In order to ensure that the algal cells can take up the carbon source, a partial pressure of 0.1–0.2 kPa in the fluid phase is necessary [26, 27], to avoid carbon limitation. A considerable amount of C-source is carbonate, which can be used by some algae via active transport. As gas turnover of the cells depends on light, a possible gradient of dissolved gases along the light path could emerge. This should usually not be a problem, especially if good mixing in this normal direction is provided according to aspect 3. More serious is the formation of a gradient of p_{O2} and p_{CO2}, accompanied by p_H between the gas inlet and gas outlet along the main flow axis of the medium especially in tubular reactors. Because of the low solubility here the oxygen is of most concern. A possibly inhibiting concentration (for some

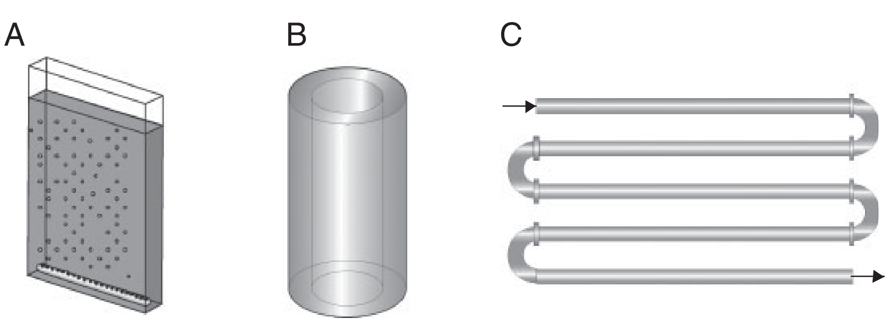

Figure 6. Most common closed photobioreactor geometries; A) flat plate reactor B) bubble column, here as annular reactor C) tubular reactor; other designs are deduced from these basic geometries. Typical surface to volume ratios are 80–100 m^2/m^3.

algae > 120% air saturation, for others > 200%) can occur already after 1 min in a tube without gas exchange.

Aspect 5: Mixing and auxiliary energy

Although volumetric mass transfer is more than 2 orders of magnitude lower in photo-bioprocesses than heterotrophic stirred tank reactors (lower biomass concentration, lower specific turnover rates) mixing is an important issue. Along the light gradient in the culture, it is known to be a key-parameter in PBR operation [28] as indicated in aspect 3. Of equal importance is enhancing mass transfer along the main axis of the reactor, which is the axial direction in tubes or the upward direction in plates and columns (aspect 4). Keeping cells from settling is in principal a minor problem but can be an issue in unfavourable designs at some positions of the reactor. The same holds for using fluid flow to prevent fouling. However, input of mechanical energy by bubbling or pumping is limited for two reasons. First, cells may be damaged or at least stressed by high local intensities of mechanical energy, second, energy supply is a major issue in production cost. Therefore, hydrodynamics is directly coupled to photosynthetic activity and therefore to biomass production. For a consistent analysis see [29]. Again high biomass concentration leads to reduction of specific energy requirements as already mentioned by Richmond [17]. Mechanical energy has to be supplied in as directed a manner as possible [30].

For proper PBR design computational fluid dynamics should be employed. A calculation example for a tubular reactor with particle trajectories [31] shows from frequency analysis that mixing in radial direction, which means along the radial light gradient, is good enough to prevent the occurrence of slow light/dark cycles. To achieve mixing with a minimum of auxiliary energy it would be favourable to limit turbulences to one specific frequency may be of several Hz. Several means have been proposed to achieve such highly defined flow patterns. For tubular reactors static helical mixers used in food industry could be useful. An application with a positive effect on productivity is shown [32] for relatively thick inclined tubes. Seemingly there is no proof yet for a possible reduction of total energy or improvement of productivity comparing to utilisation of thinner tubes or higher velocities. Evocation of Dean vortices, which are radial flow patterns in curved channels, is another option. This effect is commonly used in UV-sterilisation devices, where a transparent glass tube is wrapped around the UV-lamp thus ensuring that all volume elements come close to the lamp regularly and not only statistically. Dean vortices may play an important role in helical reactors, where commercial lab scale reactors as well as large scale installations are in operation. Radial Taylor vortices are another option. They occur in the gap between an outer static and an inner rotating cylinder under defined longitudinal flow conditions. This could be an option for improved annular reactors, although the technical expenditure is quite high. The employment of tangential flow to generate a three-dimensional swirling motion is given by [33].

Considering that only 5% of the incident radiation of the full sun spectrum is converted to chemical energy by the algal cells, the amount of mechanical energy input has to be restricted especially for production of biofuels to have a reasonable energy balance. For sunny parts of Europe for instance an annual average irradiance of about 150 W/m^2 can be considered. So energy is harvested at a rate of 7.5 W/m^2. Most outdoor reactors work with more than 50 L areal water coverage. So the (electrical) energy need for mixing is about 2.5 W/m^2 assuming 50 W/m^3, which is 30% of the harvested energy. This may be good enough for mixing (see above) considering a 12 hour dark phase with aeration switched off but not considering the energy demand for cell harvesting.

4 Commonly employed reactor designs

The complex situation of the four phase system, the different physiological demands of the cells with respect to growth and product formation kinetics, and last but not least the value of the product and its field of application has let to the development of a huge variety of closed photo-bioreactors. Together with personal preferences and experiences this has let to a situation, where the reactors seem to be different on nearly all sites on the globe. Nevertheless, a few standard designs, which are outlined below, play a major role. They have all in common a reasonable SVR. This leads directly to the fact that at least one dimension is determined by the light path length, while the other two dimensions (width and height) are free for design and scale up. A detailed description of different geometries is given from [34].

Design 1:

The flat plate reactors are surely the most robust design. Roughly speaking, two sheets have to be glued together to make a flat plate reactor with any desired light path length d in the range from a few mm up to 70 mm, resulting in SVR = 1/d for one single plate and about 50 m^{-1} for practical installations. While this reactor design has already been employed for decades, a recent comprehensive process engineering characterisation is available from Sierra [35]. Mixing and CO_2-supply is accomplished by sparging with CO_2-enriched air. For the pilot scale example reactor (0.07 m wide, 1.5 m height, 2.5 m length) the authors report air flow rates of 0.25 v/v/min leading to a mixing time of the medium of 150 s. Others [30, 36] reported even much higher aeration rates up to 2.0 v/v/min with positive effects. Power supply for bubbling was in the range of 50 W/m^3. Even in quite compact arrangements of several plates close to each other (e.g. 25 L/m^2) this value is not too high for an economically feasible production of chemical energy (biomass itself, biodiesel) by microalgae. Agitation only by bubbles seems to be the most gentle way with respect to shear stress for the algae. But this point has to checked carefully in practical applications (e.g. [30]).

A kind of horizontal plate reactor has been invented by Sato [36], Fig. 8B. The light distribution is achieved in this case by deformation of the plate to cylinders or spheres. The so-called dome shaped reactor aerated by bubbles. This is one of the rare examples, where a design has been conducted from scratch by CFD simulations. The performance has been claimed to be more than $P_G > 20.5$ g/m^2/d for one device and it is fairly mentioned, that the overall productivity for an area with several domes is only half of that value. Such specifications are missing in many other publications.

An already patented and described reactor type [37] attempts to the increase of the longitudinal mass transfer and mixing in normal direction to the plate using a purely pneumatic energy regime, Fig. 7. In this so-called flat panel airlift reactor, a directed flow is generated using the airlift principle. Cylindrical eddies are evoked using horizontal baffles as static mixers located in the interior of the panels at right angles to the flow, thus transporting the algae in a highly defined frequency from the dark to the light area. The baffles act also as light conducting structure, see below. The individual reactor modules consist of deep-drawn PVC panels. Typical modules are available from 35 L to 135 L. Further activities are under development from the company S*ubitec* (Stuttgart, Germany) into the direction of reducing specific power input to 200 W/m^3. According to company information, concentrations of over 10 g/L and average volumetric productivity of over 0.5 g/L/d were achieved where PCE was specified as 4.75 % under Central-European outdoor conditions for full sunlight spectrum. A 100 m^2 demonstration plant is under construction, with an estimated fluid volume to footprint area of 30 L/m^2.

Design 2:

Bubble columns are frequently used especially in larger lab scale for indoor experiments. To work with sufficient volume, the diameters of 20 cm and more are higher comparing to tubular reactors. This leads to considerable high dark fraction in the middle of the cylinder. This part does not contribute to productivity or has even detrimental effects on growth (aspect 3). To leave this part out of the internal reactor space the so-called annular column has been developed [8], Fig. 8. It consists of two 2-m-high acrylic cylinders of 40 and 50 cm in diameter placed one inside the other so as to form an annular chamber. The other way round, this can be seen as a wrapped flat plate reactor. It may be that the inner surface does not contribute too much to overall radiation, but for indoor applications or dark periods additional lamps could be fitted. Consequently, typical aeration rates are with 0.25 v/v/min in a similar range than those for flat plates. In a well designed study [8] to estimate areal productivities the authors measured a field of reactors using dummy cylinders to mimick mutual shading and reflection. The result was $P_G = 38\,g/m^2/d$ with PCE = 9% (PAR).

To increase axial transport the airlift principle has been employed [38]. The downcomer is usually arranged as a section of the cross-section (split cylinder) or in a coaxial inner cylinder (draft tube). In a comparison in small scale [39] reasonably good axial gas transfers have been found. As this part of the reactor is dark, the cells flow through riser and downcomer regularly, inductingan additional light/dark cycle in the range of 1–100 seconds as investigated from [40, 41]. The authors of these references did not find opposing effects on yield for low growth rates but state that no quantitative information is available for slow light/dark-cycles. The effect can be minimized by reducing the cross-section of the downcomer with respect to the riser. Also inclined airlift-reactors have been proposed [31]. However, these designs have the same problem of slow cycles. Scalability may be limited for the slower bubble velocity. To overcome this problem, gas tubes along the cultivation tubes can be used, providing multiple gassing and degassing points. In an optimal design the downcomer would also be in the illuminated side of the airlift reactor, see Fig. 7 for the flat plate airlift, where the downcomer is in the middle of the plate.

While the reported aeration rates in bubble columns and flat plates are definitely high enough to prevent sedimentation and oxygen accumulation, it is not clear, whether the benefits from fast light/dark-cycles (> 1Hz) can be gained. No reliable information is accessible, on weather the bubbles themselves induce some kind of fast mixing.

Design 3:

Tubular reactors consist of transparent tubing arranged in parallel lines coupled by manifolds, the so-called solar collector. The single tubes can be straight, they can follow a meandering course either flat on the ground or ordered in panels or coils (so called helical reactor [42–44]). The tubes have diameters of 10 to maximum 60 mm, and lengths of up to several hundred meters. The employment of tubes leads to a

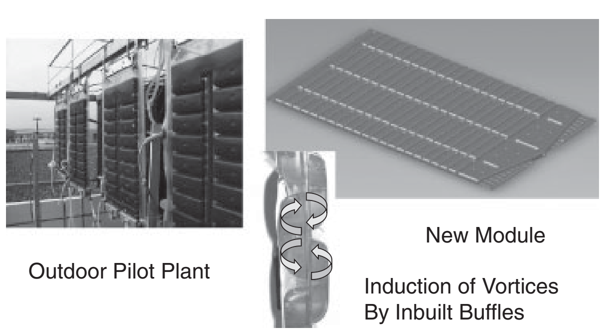

Figure 7. The flat panel airlift reactor as built by the company S*ubitec GmbH*, after [37], with kind permission of P. Ripplinger, data are given in the text.

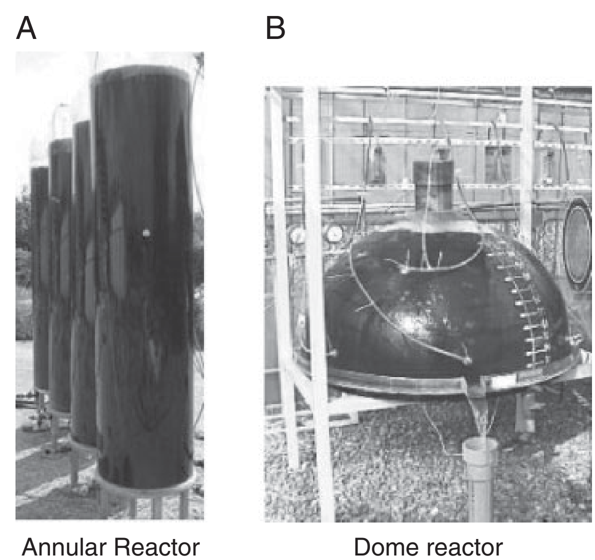

Figure 8. A) annular reactor from *F&M* (Livorno, Italy) after [8] and B) dome reactor after Sato [36], a large installation (hectars) has been build up at *BioReal* (Maui, USA).

quite high surface to volume ratio SVR over 100 m^{-1}, which is one of the main advantages of this design. Furthermore, the so called "lens" or "focussing effect" has the added advantage of homogenous light distribution. Incident light is diluted along the circumference and is in radial direction focussed onto the axis of the tube. In this way, exponential decrease of light by mutual shading of the cells is to some extent compensated by a geometrically enforced hyperbolic increase of radiation intensity. In very thin tubes, e.g. 1 cm [45] quite high biomass concentrations (see aspect 2) of more than 6 g/L can be obtained. Of course the arrangement of the tubes has to be calculated to achieve the most homogeneous incident light conditions [46]. Pumping of the medium with linear liquid velocities of 20 cm/s to 50 cm/s is either done by airlift circulators or by centrifugal pumps. Aeration and degassing is also achieved in the airlift part, while a separate gas exchange station has to be supplied along with the pumps. A velocity of more than 1 m/s will cause micro eddies of less than 50 μm diameters which potentially can damage the cells [46]. The relatively high velocity is necessary to achieve turbulent conditions leading to acceptable light/dark cycles [31]. More process engineering considerations can be found in [22, 47]. For helical reactors for example high values for volumetric productivities and efficiencies (1.5 g/L/d; PCE > 7% PAR,) have been reported [48]. The good results for tubular reactors are also underlined by [49]. They found a better performance comparing to bubble columns. However, the high energy consumption of more than 2000 W/m^3 required is surely one of the major drawbacks. For scale-up of a single tube only the diameter and the length can be considered. According to aspects 2 and 3 increase of the diameter is possible only in narrow limits, usually not more than 40 mm. Tubes with much bigger diameter (> 40 cm) have been occasionally tried out [50] but showed only low biomass concentrations and low areal and volumetric productivities, probably because the diameter is much larger than the light path length. A recently development has been taken from the market. The length coupled to residence time of the cells by liquid velocity is restricted by formation of axial gradients (aspect 4) and economy of power consumption. Molina Grima [51] gives an elaborated scale up criterion based on the light/dark cycles which are evoked by velocity dependent turbulences. While power consumption and high cost exclude tubular reactors for production e.g. of energy products, the possibility for monoseptic operation and the well defined conditions inside the reactor, make them a good choice for production of high value compounds.

Nevertheless, tube lengths of more than 100 m are good enough to build up quite big outdoor photo-bioreactors. Large installations can be found in the Negev (Israel) [52] or in Almeria [46]. Actually, the world-wide largest closed photobioreactor was erected in Klötze (Saxon-Anhalt, Germany) by *Bisantech*, following the instructions of *IGV* [53], Fig. 9. Production is carried out in glass tubes with a complete length of 500 km. The photoactive volume amounts to c. 600 m^3. Favourable temperatures were set by the conuration of the modules in a greenhouse complex with a total area of 1.2 ha, as well as suitable heating and cooling equipment. Optimum hydrodynamic conditions are created in order to avoid adherence of the micro-algae on the walls of the glass tubing (also using plastic beads) and in order to take advantage of the fast radial mixing. Sunlight provides the sole source of light and even the diffuse daylight of the winter half year is sufficient to produce a little growth. The biomass is separated currently using high performance centrifuges. The clear centrate is returned to the plant, whilst the pulpy biomass is dried with care in a spray dryer until a residual moisture content of 5% is reached. The annual production volume amounts to 100 t/a (personal communication K.-H. Steinberg, higher values not verified), thus showing a much higher areal productivity than open ponds. For open ponds areal productivities are given on an annual basis, e.g. 20 t/ha/a. For closed reactors such data are sometimes given, but is has to be stated that only in very few cases like here, closed reactors really cover one ha and have been operated for a whole year. Especially for the pilot plants given below, such values have to be taken with care. For a positive exception see [8].

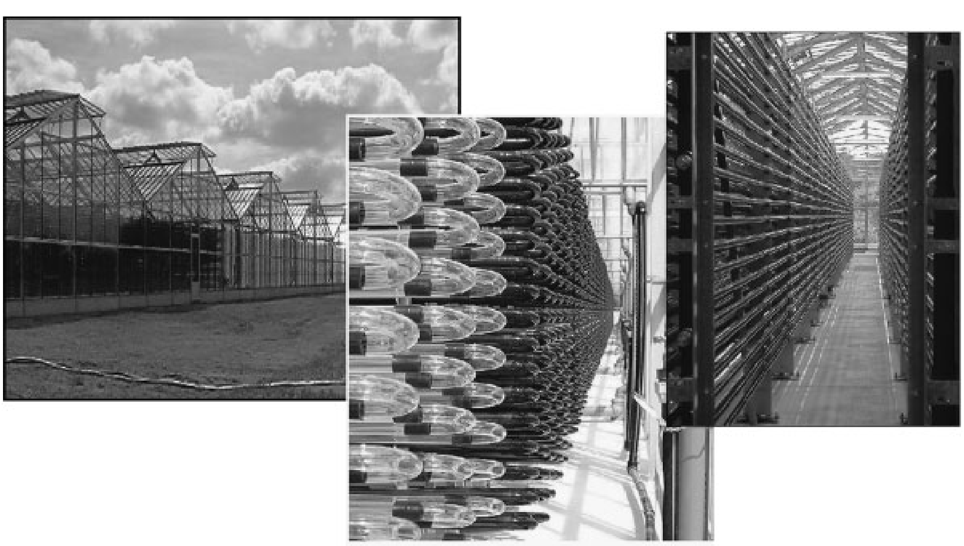

Figure 9. The world largest closed photo-bioreactor is a tubular reactor in Klötze, Germany, designed Pulz [18]. Pictures with kind permission of Bioprodukte Prof. Steinberg GmbH, data are given in the text.

5 Concepts for improved photo-bioreactor performance

Future photo-bioreactors have to be improved to allow for better photosynthetic efficiencies (PCE) close to the theoretical maximum [16], to achieve higher biomass concentrations, to reduce auxiliary energy to a minimum and to be available with low investment cost. Mass transfer seems still to be a problem [54]. While for PCE a factor of two is the highest factor to be expected, costs could go down remarkably by design and by producing the materials in large amounts.

Action 1: Measurement, Modelling, and Control

In only few recent publications process data are available for operational photo-bioreactors. In most cases these are focused on process control variables like aeration rate, CO_2-content or light intensity at the surface of the reactors. Nevertheless, more insight into the situation inside the reactors, which is actually experienced by the algae, is missing. Even in existing plants more measurement and control could be helpful [55]. In many cases - but by far not in most cases – CO_2-supply is coupled to growth e.g. via pH according to the stoichiometric demand and to the kinetics of the algae. This requires either an off-gas analyzer or an in-line sensor. Several sensors along the axes of the reactor, for tubular reactors e.g. at the beginning and at the end of a tube, could further enhance reactor performance by avoiding limitations or by reducing energy demand by over-feeding [56]. The same holds for oxygen gradients. Control of light intensity following biomass concentrations or physiological state of the cells e.g. photo-acclimatisation, may be useful (lumostatic operation investigated in [57], but can be realized in fact only in lab scale. For outdoor reactors removable shading or pivotable plates are described. It should be noted that constant irradiation per cell does not automatically mean avoidance of saturation. Nevertheless, these means are in principle coupled to a loss in overall light usage. To couple harvesting cycles to the time to diurnal light variation, reaching highest biomass concentrations at the hours of highest light intensity is a practical approach which can yield some effect.

A straight forward way to come to a rational engineering approach for photo-bioreactor design requires the simulation of three phase fluid dynamics including bubbles and cell trajectories [58–60], calculating light transfer and attenuation by ray tracing methods [61] and finally coupling these to physiological kinetic and dynamic cell models [62, 63]. In this way, possible deficiencies in axial gas transfer or the frequency of vortices can be calculated beforehand. While the simulation of three phase models including dissolved gases is not impossible with state of the art simulation tools, the microbial kinetics are usually not known. To avoid test runs in pilot scale bioreactors, a representative volume element (scale-down approach) from a simulation can be re-enact in a lab-scale reactor by applying e.g. light/dark cycles with artificial illumination [21], not designed for biomass production as such but for production of kinetic information about algae cells.

The final measure of course is to observe physiological changes in different environments. In many cases light limitation or light inhibition is investigated by measuring cell morphology or cell composition. This could be done more extensively e.g. with calorimetry or pigment content [49]. The measurement of chlorophyll and photosynthetic efficiency (F_V/F_m by PAM sensors) is becoming a standard. In current biophysical developments alga strains with reduced antenna size are developed, which should absorb only the light that can actually be used [60]. Whether or not these algae are really the solution for the light diffusion problem depends on the cell density and other factors. Actually, on-line measurement of fluorescence is an indicator for light saturation. Other input from genetics and biophysics – beside higher product formation rates and product qualities – could be algae which can not stick to walls, which show flocculation on demand for easy harvesting, or which are more tolerant to higher oxygen partial pressures. Really high biomass concentrations above e.g. 30 g/L, which can be achieved at least in lab scale, could be subject to product [62] or quorum sensing. Not much is known about these items.

Action 2: Decoupling of carbon supply and mixing

One point of energy loss is the aeration of the reactors. Enriched air has to be produced in a compressor, pumped through tubes, cleaned by membranes and finally has to be sparged against the hydrodynamic pressure. On top a small residual over pressure is needed for removal of the off-gas. A necessary primary pressure of 1.5 bar is not uncommon for flat plates and bubble columns. Another disadvantage is due to the fact, that the bubble velocity can not be influenced. The compromise between bubble residence time, bubble diameter for good gas transfer, and energy demand limits scale up seriously especially for inclined tubular devices. This has already inspired people some years ago to supply CO_2 by membrane diffusion e.g by hollow fibre modules in an external by-pass [34]. The principal advantage is shown in [64, 65]. Also dissolved oxygen can be stripped out. As in space flight cost is not that importance it can be the trend-setter for innovative photo-bioreactor design, e.g. [66–68]. In an example [69], oxygen production and removal by membranes is the main target. Nevertheless, a separate membrane module requires pumping. For large scale application the reactor wall itself should be gas-permeable (see also below). Even then some mixing will be required.

A scalable photobioreactor system for efficient production has been described by Willson [70], solix reactor in Fig. 10. In various embodiments, this system combines increased surface areas to reduce light intensity, an external water basin to provide structural support and thermal regulation at low cost,

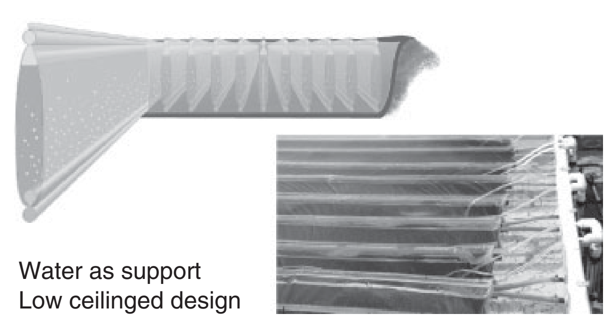

Figure 10. G3 reactor from *solix* [70], with kind permission of B. Willson.

and membranes for gas exchange. It consists of flexible plastic or composite panels that are joined together to make triangular or other cross-sectional geometries when partially submerged in water. So basic designs demands given above are combined here, including a horizontal low-ceilinged installation without panels which would need frameworks or racks and without the necessity of an expensive external green house. Productivities in the range up to 30 g/l are reported and will be published in an upcoming paper [70].

Action3: Increase of inner surface

One way of coming closer to better performances is to enlarge not the outer surface but to enlarge the inner surface by built-in transparent components into the internal reactor volume. This is to dilute the light over a large internal surface, having only thin liquid layers and saving material. Several patents in that direction have been granted or filed. Among these are ligaments, bars or side-emitting glass fibres inside tubes or plates [71]. Although the argument to increase light penetration depth with such fixtures is a bit misleading, the basic point is to enlarge the surface area of the reactor. One recent example comes from [72]. Here sunlight is captured by linear Fresnel lenses and led into vertical plastic light guides from where it eventually scatters out into flat panel photo-bioreactor compartments. The compartments are separated by water jackets. The panel itself is mounted horizontally on the surface thereby collecting all the sunlight falling onto a given area. Furthermore, it can be imagined that such a horizontal construction is more robust than vertical panels, considering football field scaled systems and even larger areas which are required for energy and food production. The light capturing process is supported by a possible rotation of the lenses following the direction of the sun. Therefore, the so called Green Solar Collector (GSC) is a light- and area-efficient design.

Finally, one alternative to the paradigm of bringing the algae to the light over the largest and most transparent surface possible is the approach of bringing the light to the algae. This could finally lead to the employment of milli- and micro-scaled multi-layered structures, see Fig. 5. The Immobilization of algae on a fleece of glass fibres is one extreme example. Alternative suggestion are made, including gathering sunlight via suitable antennae, using light conductive structures to guide the light into a compact and closed reactor, where it is then diffused via laterally emitting fibres or panels [73], Fig. 11. This entails a very big advantage: the temperature of the reactor chamber can be maintained at an appropriate level, pO_2, pCO_2, and pH can be regulated and above all the reactor can be sterilized and run monoseptically. Operation under pressure is also conceivable. In addition, when employed outside, all the collecting units that come into question such as Fresnel lenses, solar collectors and fibre glass are more weather-resistant in comparison to reactor panels. Furthermore, the radiation components not required, such as infrared can be uncoupled much more effectively and used separately for energy recovery. A study for such so called hybrid reactor type is given by Janssen [6]. Using present materials the light guides themselves suffers from losses to the scale of 50%. Furthermore, at the moment the system is too expensive to be economically feasible, considering the huge amount of glass fibres or the inner surface area, which has to be much larger

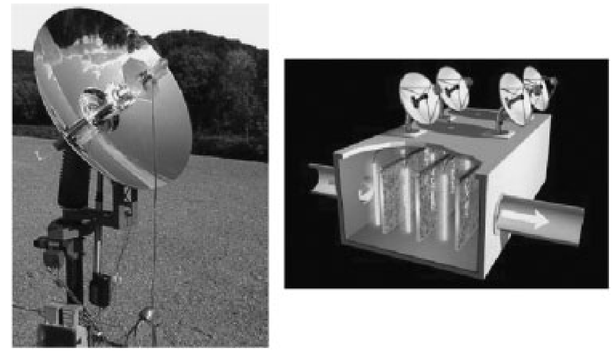

Figure 11. Hybrid reactor as presented from ORNL/Ohio University Project (Hybrid Lighting) after [63].

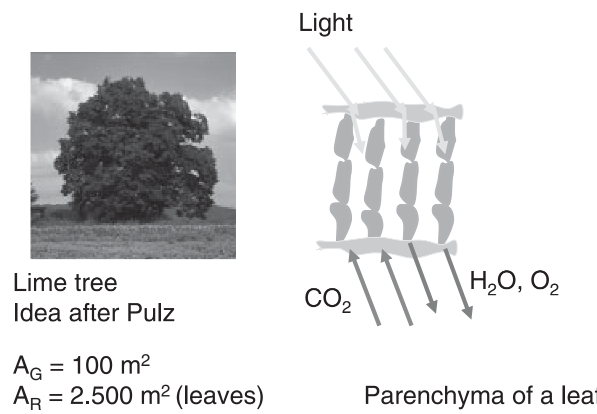

Figure 12. The tree as a model for photo-bioreactors; it has a high surface to volume ratio and provides air channels for gas flow and diffusion.

than the light collecting area (aspect 1). This principle was brought into action for the first time with components, which were originally conceived for the illumination of office space in high-rise buildings, see Fig. 11. This technology is far from operational. However, given further progress in the area of light design and the materials involved, the possible advantages are so high that this approach should be followed with interest.

Greenfuel has operated a special photo-bioreactor, which in principle consists of two bubble columns. These are connected on the underside via a cross tube and a shared head/degassing chamber on the upper side. Precise setting of the aeration in both tubes produces a circular flow of the medium, similar to that produced by an airlift reactor with exterior downcomers. As only the front column is transparent, the algae pass through a light/dark phase. The front column is set with a specific angle so that the rising bubbles rise predominantly on the side turned towards the light. This produces fast vortices which supports the physiological advantages of fast cycles and provides an additional mass transfer. This effect can be supported using light conducting components. The reactor was developed in co-operation with MIT and operated on the compound of the Redhawk Power Station close to Phoenix, Arizona. In a study [74] Pulz claims very high productivities for this reactor, of a mean of 98 $g/m^2/d$. Peak values are given as reaching 170 g/m^2/d, which should be due to the high SVR > 1000. The author states that better gas and yield management could lead to values clearly exceeding 100 g/m^2/d at least for a few weeks. Concrete values for the requirement of auxiliary energy are not stated, and more advanced data is not to be found in any other source. However based on this information this facility seems to consist of one of the most productive photo-bioreactors described so far.

Action 4: Learning from nature

Microalgae exhibit a high PCE of 5% in comparison to terrestrial plants of 1% [75]. Cultivation in closed bioreactors offers some advantages over agriculture. Nevertheless the bioreactor has to be available for reasonable cost. Even a glass house to protect a photo-bioreactor with cheap materials would be much too expensive. Recent feasibility studies ([76, 77]) see an economic viable value only for reactor costs below 40/m^2. On the other hand, a normal tree does not need a reactor. It manages all problems of mass transfer, light distribution, water pumping, and even solid/liquid separation by itself. That inspired Pulz [53] to compare reactor design with a tree. The concept of large SVR is realized by the large surface of the leaves. Furthermore, the leaves are quite thin. Looking through a microscope we can discover additional principles which could be considered for reactor design. The leaves are micro-structured to distribute the light not only over the surface of the leaves but to distribute it along light guiding structures to the photosynthetically active cells. Gas transfer is not done by bubbling but by diffusion only. Differently from applying membranes to macroscopic compartments, the plant provides gas transport channels until finally the cell membranes offer a huge surface for diffusive transport.

6 Concluding remarks

The design of photo-bioreactors in commercial scale has made good progress in the last decade. The basic principles have been extensively developed into designs with relatively high efficiencies. Suitable process engineering calculation methods have been published to give a quantitative understanding of mass and light transfer. But none of the existing pilot plants have proven economical on a large scale [9]. While even here the last word is not spoken, the consideration of physiological demands of the algae is still far from being resolved. The calculation of optimum plate gauges or light distribution factors is also not fully characterised on the basis of measured growth or product formation kinetics. Of course, compromises have to be made to end up with robust and all-purpose reactor types. Also practical questions, which are not considered in this review, for example for the best material with respect to price, life span or tendency for fouling, are not fully answered to general contentment. Actually several start-ups have already become bankrupted due to exaggerated expectations. The reason behind this development is that the companies are not considering all the challenges and barriers that need to be overcome before this technology can be commercialized, Darzins, cited after [9]. Development in process engineering is one hurdle which can not be avoidedon the way from the algae cell to large scale production.

However the rapid increase of interest and investment in algae for production of biodiesel, biomethane or hydrogen has brought additional considerations and demands to photo-bioreactor design. First is the cost, which has to drop down below 40 €/m^2 to allow for an economically feasible production of bioenergy by algae. This prohibits for example the use of greenhouses to cover the reactors. The second item is the use of auxiliary energy for mixing and gas transfer. This should ideally not exceed 2 W/m^2 which corresponds to approximately 50 W/m^3. As a third demand biomass concentration has to be at least better than 20 g/L. So in all three aspects the performance has to increase by roughly speaking a factor 3 comparing to current standards. This goal is not so far from reality. Further consequent application of quantitative engineering approaches is one thing. While we speak about square-kilometres of algae farms, industrial production of transparent films or tubes with milli- or mikro-structures and several layers of different materials will replace handmade constructions consisting of components from the hardware store. Furthermore, a paradigm shift can already be observed, leading to the route of bio-degradable one way reactors or to the route of highly structured intelligent production systems. Even high-tech materials could become cheap when needed in really large amounts. A key parameter for achievement of this goal is the fine tuning of the conditions inside the reactor with respect to the kinetics and dynamics of the respected cells.

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Conflict of interest

The authors have declared no conflict of interest.

References

[1] M. A. Borowitzka, Commercial production of microalgae: ponds, tanks, tubes and fermenters. *J. Biotechno.*, **1999**. *70(1–3)*, 313–321.

[2] E. M. Grima, F. G. A. Acién Fernández, F. G. Garcia Camacho, Y. Chisti, Photobioreactors: light regime, mass transfer, and scaleup. *J. Biotechnol.*, **1999**. *70(1–3)*, 231–247.

[3] A. S. Miron, A. C. Gomez, F. G. Garcia Camacho, E. M. Grima, Y. Chisti, Comparative evaluation of compact photobioreactors for large-scale monoculture of microalgae. *J. Biotechnol.*, **1999**. *70(1–3)*, 249–270.

[4] Y. K. Lee, Microalgal mass culture systems and methods: Their limitation and potential. *J. Appl. Phycol.*, **2001**. *13(4)*, 307–315.

[5] I. S. Suh, C. G. Lee, Photobioreactor engineering: Design and performance. *Biotechnology and Bioprocess Engineering*, **2003**. *8*(*6*), 313–321.

[6] M. Janssen, J. Tramper, L. R. Mur, R. H. Wijffels, Enclosed outdoor photobioreactors: Light regime, photosynthetic efficiency, scale-up, and future prospects. *Biotechnol. Bioeng.*, **2003**. *81*(*2*), 193–210.

[7] B. Hankamer, F. Lehr, J. Rupprecht, J. H. Mussgnug, C. Posten, O. Kruse, Photosynthetic biomass and H-2 production by green algae: from bioengineering to bioreactor scale-up. *Physiologia Plantarum*, **2007**. *131*(*1*), 10–21.

[8] G. C. Zittelli, L. Rodolfi, N. Biondi, M. R. Tredici, Productivity and photosynthetic efficiency of outdoor cultures of Tetraselmis suecica in annular columns. *Aquaculture*, **2006**. *261*(*3*), 932–943.

[9] E. Waltz, Biotech's green gold?. *nature biotechnology*, **2009**. *27*, 15–18.

[10] R. Rosello-Sastre, Kopplung physiologischer und verfahrenstechnischer Parameter beim Wachstum und bei der Produktbildung der Rotalge Porphyridium purpureum. *Dissertation, Karlsruhe Institute of Technology*, **2009**.

[11] A. Melis, J. Neidhardt, J. R. Benemann, Dunaliella salina (Chlorophyta) with small chlorophyll antenna sizes exhibit higher photosynthetic productivities and photon use efficiencies than normally pigmented cells. *J. Appl. Phycol.* **1999**, *10*, 515–525.

[12] J. H. Mussgnug, S. Thomas-Hall, J. Rupprecht, A. Foo, V. Klassen, A. McDowall, P. M. Schenk, O. Kruse, B. Hankamer, Engineering photosynthetic light capture: impacts on improved solar energy to biomass conversion. *Plant Biotechnology Journal*, **2007**. *5*(*6*), 802–814.

[13] J. U. Grobbelaar, N. Kurano, Use of photoacclimation in the design of a novel photobioreactor to achieve high yields in algal mass cultivation. *J. Appl. Phycol.* **2003**. *15*(*2–3*), 121–126.

[14] I. S. Suh, H. N. Joo, C. G. Lee, A novel double-layered photobioreactor for simultaneous Haematococcus pluvialis cell growth and astaxanthin accumulation. *J. Biotechnol.*, **2006**. *125*(*4*), 540–546.

[15] J. F. Cornet, C. G. Dussap, J. B. Gros, C. Binois, C. Lasseur, A Simplified Monodimensional Approach for Modeling Coupling between Radiant Light Transfer and Growth-Kinetics in Photobioreactors. *Chemical Engineering Science*, **1995**. *50*(*9*), 1489–1500.

[16] X. G. Zhu, S. P. Long, D. R. Ort, What is the maximum efficiency with which photosynthesis can convert solar energy into biomass?, *Current opinion in biotechnology*, **2008**. *19*, 153–159.

[17] A. Richmond, C. W. Zhang, Y. Zarmi, Efficient use of strong light for high photosynthetic productivity: interrelationships between the optical path, the optimal population density and cell-growth inhibition. *Biomolecular Engineering*, **2003**. *20*(*4–6*), 229–236.

[18] O. Pulz, W. Gross, Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology*, **2004**. *65*(*6*), 635–648.

[19] V. Tichy, M. Poulson, J. U. Grobbelaar, F. Xiong, L. Nedbal, Photosynthesis, growth and photoinhibition of microalgae exposed to intermittent light. *Photosynthesis: From Light to Biosphere*, **1995**, *5*, 1029–1032.

[20] J. Grobbelar, L. Neddal, V. Tichy, Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photo acclimated to different light intensities and implications for mass algal cultivations. *J. Appl. Phycol.*, **1996**, *8*, 335–343.

[21] R. R. Rosello Sastre, Z. Coesgoer, I. Perner-Nochta, P. Fleck-Schneider, C. Posten, Scale-down of microalgae cultivations in tubular photo-bioreactors - A conceptual approach. *J. Biotechnol.*, **2007**. *132*(*2*), 127–133.

[22] E. Molina Grima, J. Acién Fernández, F. G. Acien, Y. Chisti, Tubular photobioreactor design for algal cultures. *J. Biotechnol.*, **2001**. *92*(*2*), 113–131.

[23] M. Janssen, P. Slenders, J. Tramper, L. R. Mur, R. H. Wijffels, Photosynthetic efficiency of Dunaliella tertiolecta under short light/dark cycles. *Enzyme and Microbial Technology*, **2001**. *29*(*4–5*), 298–305.

[24] N. Zou, A. Richmond, Light-path length and population density in photoacclimation of Nannochloropsis sp (Eustigmatophyceae). *J. Appl. Phycol.*, **2000**. *12*(*3–5*), 349–354.

[25] N. Yoshimoto, T. Sato, Y. Kondo, Dynamic discrete model of flashing light effect in photosynthesis of microalgae. *J. Appl. Phycol.*, **2005**. *17*(*3*), 207–214.

[26] J. Doucha, F. Straka, K. Livansky, Utilization of flue gas for cultivation of microalgae (Chlorella sp.) in an outdoor open thin-layer photobioreactor. *J. Appl. Phycol.*, **2005**. *17*(*5*), 403–412.

[27] M. H. Spalding, Microalgal carbon-dioxide-concentrating mechanisms: Chlamydomonas inorganic carbon transporters. *J. Exp. Bot.*, **2008**, *59*,1463–1473.

[28] J. Pruvost, L. Pottier, J. Legrand, Numerical investigation of hydrodynamic and mixing conditions in a torus photobioreactor. *Chemical Engineering Science*, **2006**. *61*(*14*), 4476–4489.

[29] J. Pruvost, J. F. Cornet, J. Legrand, Hydrodynamics influence on light conversion in photobioreactors: An energetically consistent analysis. *Chemical Engineering Science*, **2008**. *63*(*14*), 3679–3694.

[30] C. B. Alias, M. C. G. M. Lopez, F. G. A. Acién Fernández, J. M. G. Sevilla, J. L. G. Sanchez, E. M. Grima, Influence of power supply in the feasibility of Phaeodactylum tricornutum cultures. *Biotechnol. Bioeng.*, **2004**. *87*(*6*), 723–733.

[31] I. Perner-Nochta, C. Posten, Simulations of light intensity variation in photobioreactors. *J. Biotechnol.*, **2007**. *131*(*3*), 276–285.

[32] C. U. Ugwu, J. C. Ogbonna, H. Tanaka, Light/dark cyclic movement of algal culture (Synechocystis aquatilis) in outdoor inclined tubular photobioreactor equipped with static mixers for efficient production of biomass. *Biotechnology Letters*, **2005**. *27*(*2*), 75–78.

[33] A. Muller-Feuga, J. Pruvost, R. Le Guedes, L. Le Dean, P. Legentilhomme, J. Legrand, Swirling flow implementation in a photobioreactor for batch and continuous cultures of Porphyridium cruentum. *Biotechnol. Bioeng.*, **2003**. *84*(*5*), 544–551.

[34] A. P. Carvalho, L. A. Meireles, F. X. Malcata, Microalgal reactors: A review of enclosed system designs and performances. *Biotechnology Progress*, **2006**. *22*(*6*), 1490–1506.

[35] E. Sierra, F. G. Acien, J. M. Acién Fernández, J. L. Garcia, C. Gonzalez, E. Molina Grima, Characterization of a flat plate photobioreactor for the production of microalgae. *Chemical Engineering Journal*, **2008**. *138*(*1–3*), 136–147.

[36] C. H. Wang, Y. Y. Sun, R. L. Xing, L. Q. Sun, Effect of liquid circulation velocity and cell density on the growth of Parietochloris incisa in flat plate photobioreactors. *Biotechnol. Bioproc. Eng.*, **2005**. *10*(*2*), 103–108.

[37] J. Degen, A. Uebele, A. Retze, U. Schmid-Staiger, W. Trosch, A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect. *J. Biotechnol.*, **2001**. *92*(*2*), 89–94.

[38] A. S. Miron, F. G. Garcia Camacho, A. C. Gomez, E. M. Grima, Y. Chisti, Bubble-column and airlift photobioreactors for algal culture. *Aiche Journal*, **2000**. *46*(*9*), 1872–1887.

[39] S. Oncel, F. V. Sukan, Comparison of two different pneumatically mixed column photobioreactors for the cultivation of Artrospira platensis (Spirulina platensis). *Bioresource Technology*, **2008**. *99*(*11*), 4755–4760.

[40] M. J. Barbosa, M. Janssen, N. Ham, J. Tramper, R. H. Wijffels, Microalgae cultivation in air-lift reactors: Modeling biomass yield and growth rate as a function of mixing frequency. *Biotechnol. Bioeng.*, **2003**. *82*(*2*), 170–179.

[41] M. Janssen, M. Janssen, M. de Winter, J. Tramper, L. R. Mur, J. Snel, R. H. Wijffels, Efficiency of light utilization of Chlamydomonas reinhardtii under medium-duration light/dark cycles. *J. Biotechnol.*, **2000**. *78*(*2*), 123–137.

[42] M. Morita, Y. Watanabe, T. Okawa, H. Saiki, Photosynthetic productivity of conical helical tubular photobioreactors incorporating Chlorella sp under various culture medium flow conditions. *Biotechnol. Bioeng.*, **2001**. *74*(*2*), 136–144.

[43] D. O. Hall, F. G. A. Acién Fernández, E. C. Guerrero, K. K. Rao, E. M. Grima, Outdoor helical tubular photobioreactors for microalgal production: Modeling of fluid-dynamics and mass transfer and assessment of biomass productivity. *Biotechnol. Bioeng.*, **2003**. *82*(*1*), 62–73.

[44] F. G. A. Acién Fernández, D. O. Hall, E. C. Guerrero, K. K. Rao, E. M. Grima, Outdoor production of Phaeodactylum tricornutum biomass in a helical reactor. *J. Biotechnol.*, **2003**. *103*(*2*), 137–152.

[45] P. Carlozzi, Dilution of solar radiation through "culture" lamination in photobioreactor rows facing South-North: A way to improve the efficiency of light utilization by cyanobacteria (Arthrospira platensis). *Biotechnol. Bioeng.*, **2003**. *81*(*3*), 305–315.

[46] F. G. A. Acién Fernández, J. M. F. Sevilla, J. A. S. Perez, E. M. Grima, Y. Chisti, Airlift-driven external-loop tubular photobioreactors for outdoor production of microalgae: assessment of design and performance. *Chemical Engineering Science*, **2001**. *56*(*8*), 2721–2732.

[47] R. W. Babcock, J. Malda, J. C. Radway, Hydrodynamics and mass transfer in a tubular airlift photobioreactor. *J. Appl. Phycol.*, **2002**. *14*(*3*), 169–184.

[48] M. Morita, Y. Watanabe, H. Saiki, Photosynthetic productivity of conical helical tubular photobioreactor incorporating Chlorella sorokiniana under field conditions. *Biotechnol. Bioeng.*, **2002**. *77*(*2*), 155–162.

[49] M. C. G. M. Lopez, E. D. Sanchez, J. L. C. Lopez, F. G. A. Acién Fernández, J. M. F. Sevilla, J. Rivas, M. G. Guerrero, E. M. Grima, Comparative analysis of the outdoor culture of Haematococcus pluvialis in tubular and bubble column photobioreactors. *J. Biotechnol.*, **2006**. *123*(*3*), 329–342.

[50] M. Olaizola, Commercial Development of microalgal biotechnology: from the test tube to the marketplace. *Biomol. Eng.*, **2003**, *20*, 459–466.

[51] E. M. Molina Grima, F. G. Acién Fernández, F. G. Garcia Camacho, F .C. Rubio, Y. Chisti, Scale-up of tubular photobioreactors. *J. Appl. Phycol.*, **2000**. *12*(*3–5*), 355–368.

[52] S. Boussiba, C. Aflalo, An insight into the future of microalgae biotechnology. *Innovation in Food Technology*, **2005**. *28*, 37–39.

[53] O. Pulz, Photobioreactors: production systems for phototrophic microorganisms. *Applied Microbiology and Biotechnology*, **2001**. *57*(*3*), 287–293.

[54] C. U. Ugwu, H. Aoyagi, H. Uchiyama, Photobioreactors for mass cultivation of algae. *Bioresource Technology*, **2008**. *99*(*10*), 4021–4028.

[55] N. T. Eriksen, The technology of microalgal culturing. *Biotechnology Letters*, **2008**. *30*(*9*), 1525–1536.

[56] D. Soletto, L. Binaghi, L. Ferrari, A. Lodi, J. C. M. Carvalho, M. Zilli, A. Converti, Effects of carbon dioxide feeding rate and light intensity on the fed-batch pulse-feeding cultivation of Spirulina platensis in helical photobioreactor. *Biochemical Engineering Journal*, **2008**. *39*(*2*), 369–375.

[57] H. S. Lee, Z. H. Kim, S. E. Jung, J. D. Kim, C. G. Lee, Specific light uptake rate can be served as a scale-up parameter in photobioreactor operations. *Journal of Microbiology and Biotechnology*, **2006**. *16*(*12*), 1890–1896.

[58] H. P. Luo, M. H. Al-Dahhan, Analyzing and modeling of photobioreactors by combining first principles of physiology and hydrodynamics. *Biotechnol. Bioeng.*, **2004**. *85*(*4*), 382–393.

[59] I. Perner-Nochta, A. Lucumi, C. Posten, Photoautotrophic cell and tissue culture in a tubular photobioreactor. *Engineering in Life Sciences*, **2007**. *7*(*2*), 127–135.

[60] G. Vunjak-Novakovic, Y. Kim, X. X. Wu, I. Berzin, J. C. Merchuk, Air-lift bioreactors for algal growth on flue gas: Mathematical modeling and pilot-plant studies. *Industrial & Engineering Chemistry Research*, **2005**. *44*(*16*), 6154–6163.

[61] J. W. F. Zijffers, S. Salim, M. Janssen, J. Tramper, R. H. Wijffels, Capturing sunlight into a photobioreactor: Ray tracing simulations of the propagation of light from capture to distribution into the reactor. *Chemical Engineering Journal*, **2008**. *145*(*2*), 316–327.

[62] P. Fleck-Schneider, F. Lehr, C. Posten, Modelling of growth and product formation of Porphyridium purpureum. *J. Biotechnol*, **2007**. *132*(*2*), 134–141.

[63] J. C. Merchuk, F. Garcia-Garcia Camacho, E. Molina-Grima, Photobioreactor design and fluid dynamics. *Chemical and Biochemical Engineering Quarterly*, **2007**. *21*(*4*), 345–355.

[64] L. H. Cheng, L. Zhang, H. L. Chen, C. J. Gao, Carbon dioxide removal from air by microalgae cultured in a membrane-photobioreactor. *Separation and Purification Technology*, **2006**. *50*(*3*), 324–329.

[65] L. H. Fan, Y. T. Zhang, L. H. Cheng, L. Zhang, D. S. Tang, H. L. Chen, Optimization of carbon dioxide fixation by

Chlorella vulgaris cultivated in a membrane-photo-bioreactor. *Chemical Engineering & Technology*, **2007**. *30*(*8*), 1094–1099.

[66] F. Godia, J. Albiol, J. L. Montesinos, J. Perez, N. Creus, F. Cabello, X. Mengual, A. Montras, C. Lasseur, MELISSA: a loop of interconnected bioreactors to develop life support in space. *J. Biotechnol*, **2002**. *99*(*3*), 319–330.

[67] W. Ai, S. Guo, L. Qin, Y. Tang, Development of a ground-based space micro-algae photo-bioreactor. *Advances in Space Research*, **2008**. *41*(*5*), 742–747.

[68] K. Slenzka, M. Dünne, B. Jastorff, Biomonitoring and risk assessment on earth and during exploratory missions using AquaHab®. *Advances in Space Research*, **2008**. *42*(*12*), 1944–1950.

[69] G. Cogne, J. F. Cornet, J. B. Gros, Design, operation, and modeling of a membrane photobioreactor to study the growth of the cyanobacterium Arthrospira platensis in space conditions. *Biotechnology Progress*, **2005**. *21*(*3*), 741–750.

[70] B. Willson, G4 photobiorector. under review, 2009.

[71] J. C. Ogbonna, T. Soejima, H. Tanaka, An integrated solar and artificial light system for internal illumination of photobioreactors. *J. Biotechnol.*, **1999**. *70*(*1–3*), 289–297.

[72] J. W. F. Zijffers, M. Janssen, J. Tramper, R. H. Wijffels, Design process of an area-efficient photobioreactor. *Marine Biotechnology*, **2008**. *10*(*4*), 404–415.

[73] C. Y. Chen, G. D. Saratale, C. M. Lee, P. C. Chen, J. S. Chang, Phototrophic hydrogen production in photobioreactors coupled with solar-energy-excited optical fibers. *Int. J. Hydrogen Energy.*, **2008**, *33*, 6886–6895.

[74] O. Pulz, Performance Summary Report: Evaluation of GreenFuel's 3D Matrix Algae Growth Engineering Scale Unit. 2007.

[75] X. G. Zhu, S. P. Long, D. R. Ort, What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Current Opinion in Biotechnology*, **2008**, *19*,153–159.

[76] P. E. Zemke, B. D. Wood, D. J. Dye, D. J. Bayless, J. D. Muhs, Economic analysis of a vertical sheet algal photobioreactor for biodiesel production. *Proceedings of the Energy Sustainability Conference* **2007**, *2007*, 815–820.

[77] B. Hankamer, P. Schenk, U. Marx, C. Posten, O. Kruse, The solar bio-fuels consortium: Developing advanced bio-fuel production systems. *Photosynthesis Research*, **2007**. *91*(*2–3*), 136–136.

[78] J. C. Merchuk, Y. Rosenblat, I. Berzin, Fluid flow and mass transfer in a counter-current gas-liquid inclined tubes photo-bioreactor. *Chemical Engineering Science*, **2007**. *62*(*24*), 7414–7425.

[79] J. C. Merchuk, X. Wu, Modeling of photobioreactors: Application to bubble column simulation. *J. Appl. Phycol.*, **2003**. *15*(*2–3*), 163–170.

[80] D. Beshears, D. Earl, J. Muhs, C. Maxey, G. Capps, S. Stellern, P. D. Bayless, S. Switzer, First generation Hybrid Solar Lighting Collector System development and operating experience. *Nonimaging Optics: Maximum Efficiency Light Transfer Vii*, **2003**. *5185*, 56–66.

[81] T. Sato, S. Usui, Y. Tsuchiya, Y. Kondo, Invention of outdoor closed type photobioreactor for microalgae. *Energy Conversion and Management*, **2006**. *47*(*6*), 791–799.

[82] M. R. Tredici, Mass Production of Microalgae: Photobioreactors. In: A. Richmond (Ed.) *Handbook of Microalgal Culture*, Blackwell, Oxford, **2004**, 178–214.

[83] L. Rodolfi, G. Chini Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, M. R. Tredici, Microalgae for Oil: strain Selection, Induction of lipid Synthesis and Outdoor Mass Cultivation in a Low-Cost Photobioreactor. *Biotechnol. Bioeng.*, **2009**. *102*(*1*), 100–112.

[84] B. Hankamer, F. Lehr, J. Rupprecht, J. H. Mussgnug, C. Posten, O. Kruse, Photosynthetic biomass and H2 production by green algae: from bioengineering to bioreactor scale-up. *Physiologia Plantarum*, **2007**, *131*, 10–21.

[85] L. Nedbal, M. Trtilek, J. Cerveny, O. Komarek, H. B. Pakrasi, A photobioreactor system for precision cultivation of photoautotrophic microorganisms and for high-content analysis of suspension dynamics. *Biotechnol. Bioeng.*, **2008**, *100*(*5*), 902–910.

