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Technical evaluation of photobioreactors for microalgae cultivation

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Abstract. This paper undertakes the description and assessment of various solutions applied for the design of photobioreactors as the type of apparatus, which can provide high output of green algae biomass. The design of such apparatus plays an important role in the context of the concurrent fulfillment of ecological and economic requirements, which are necessary to conduct an efficient and effective technology using cheap and easily accessible resources to produce different goods. Nowadays, algae is seen as one of the most promising sustainable way to produce energy in the future (biofuels, electricity, thermal energy) but technologies of biomass production and processing are still under development particularly to increase biomass and energy output. The cultivation costs in closed systems are still high, limiting their commercial applications to high-valued compounds but they can be reduced by efficient bioreactor designs, which are able to achieve high areal biomass productivities. This paper focuses on the advantages and drawbacks associated with the application of the particular types of bioreactors in algae production, description of their operation parameters and area for practical application, pointing of the constructions (tubular, flat panel, bubble column) that can contribute to improvement the profitability of large-scale production.

1 Introduction

Uncontrolled anthropogenic activities and technological revolution increase fossil fuel consumption at higher rate that prompted research related to the search for alternative energy sources to cover the current need and future demand of energy. In last few decades biomass of terrestrial crops has been studied as a promising source of renewable energy but large scale production is still debatable issue because of indirect use of fossil fuel, lower productivity, lack of availability of land which are usually intended for food production. These limitations of land based systems fetch opportunity to look into untapped potential energy source such as algae.

Nowadays algae are considered not only as a valuable organic resource with a potential application in the production of a wide range of products, starting with foodstuffs and animal feed, through beauty products, pigments and pharmaceuticals to fertilizers for agriculture and isotopically labeled compounds but as a source of biodiesel, biogas and potentially important component of the wastewater treatment system [1-8]. The current technologies applied for biofuel production on the basis of algae are not sufficiently effective and economically viable so as to be able to prove competitive in comparison to the existing solutions in petrochemical industry based on the use of renewable resources. However, in the consideration of the growing problems of the transport sector and the requirements associated with effective gaining resources for various industry branches, new ideas with regard to the use of integrated biomass cultivation and processing systems are bound to develop continuously. The effective production and processing systems are going to be determined by the development of advanced apparatus, which can provide reduction of the production cost and increase of its competitiveness in relation to the conventional systems.

Due to their small size, measured in micrometers, microalgae are cultivated in dedicated land installations [9-11] and ones that float on a water surface [12]. The open systems, including natural reservoirs (lagoons, lakes) and ponds (raceway ponds) are listed among the oldest configurations used in industry processes designed for production of microalgae [1,8-9,13]. At present, around 90% of the global algae production is conducted in the open systems [14-15]. Estimates indicate that the global annual production of microalgal biomass is equal to 15,000 tonnes of dry mass with the market value in the range from 30 to 300 euro per kilo [16].

The typical open systems of algae cultivation require large areas with considerable light exposition; hence, they are common on desert places, where there is no competition of agricultural production designed for food production purposes. Concrete and PVC tanks are relatively cheap to build and service, however, they production capabilities are limited, e.g. the production capabilities of *Chaetocereos* microalgae is equal to only 300,000 cells$\cdot$ml^{-1} [17]. Apart from this, open systems in algae farms are susceptible to water loss from

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evaporation and in desert places another problem is associated with the sand carried by sandstorms and volcanic ash transported with the wind over long distances (estimated at 1–10 ton·km^{-2}·month^{-1}). Parasites (including mites and competing algae strains) can easily enter the cultivation and cause a serious threat to the biosecurity of the farm due to the lack of safety measures in the vessel installations. In addition, in the areas with high level of insolation, the incident light (>100,000 lux) can led to the thermal shock and algal cells bleaching, which causes the decrease of production efficiency [7, 17]. In this respect, microalgae cultivation conducted in the closed system (photobioreactors) can prove to be more effective. This is due to the possibility of better control over the production process (temperature, light, pH, CO_2 concentration) and the potential increase of the productivity by several and even a dozen times compared to the open systems [18].

The efficiency ratio of biomass in relation to the substrate and its productivity (i.e. parameters representing the economic efficiency of production) are higher in the closed systems compared to the farms consisting of open tanks [19]. Wijffels et al. [20] report that the productivity of closed systems can be as much as 40–80 tonnes of dry mass per hectare per year accompanied by a comparable cost of production in both cultivation systems [19]. One can note, however, that in large photobioreactor systems forming outdoor installations, the productivity of algal biomass can vary depending on the scale of production [2]. For example, the productivity of *Haematococcus pluvialis* algae at a level of 0.05 g·l^{-1}·d^{-1} can be achieved both in the cultivation conducted in a tube bioreactor with the capacity of 25,000 l as well as in a 55 liters bubble column [21-22]. The productivity of algae cultivation is relative to the applied technology and farm location, design of the photobioreactor, strain as well as sensitivity of the algae to the external environment [23].

Bubble column and airlift photobioreactor designs, as well as others, such as fermenter, flat panel and spiral tube designs are more complex than the open equivalents, and the cultivations realized in them are considered as much more cost-intensive [9,16]. Such a cost is associated with the necessity of gaining sufficient space inside the room for installations, higher energy consumption, need of medium sterilization and the necessary service cost conducted by staff with adequate skills and qualifications. Some of the photobioreactor types cannot be applied for algae cultivation on an industrial scale due to the scale and exploitation problems (clogging of pipelines and limited light penetration) [24-25]. The majority of this apparatus also requires the application of artificial indoor lighting, which leads to an increase in energy consumption followed by an increase of the operation cost of the installation [15,24,26].

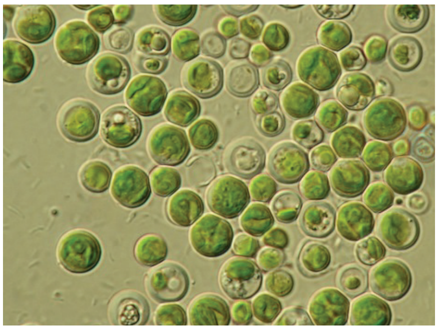
The up-to-date, sustainable and environmentally-friendly designs of photobioreactors in terms of the use of technical solutions and technology include a number of combined technologies of algae processing. This, in turn provides their application both in environmental protection (for wastewater treatment, bioremediation, CO_2 sequestration), as well as a source of valuable substances with a potential use in various industrial branches and agriculture [12,27]. The currently built biorefineries with algae processing capabilities are able to concurrently produce biodiesel, animal feed, biogas and electricity [28]. The intensive development of algae biotechnology is aimed at the improvement of large-scale algae production in cost-intensive closed cultivation systems. In connection with this, the studies conducted nowadays focus primarily on the search for more and more effective microorganism strains, their genetic modifications, optimization of the design and the operation of various reactor types in order to ensure the high productivity of algal biomass [16,23]. Apart from this, activities are undertaken with the aim of reducing the high cost associated with the investment and fluid pumping, light demand, cooling, draining and drying of biomass in such a manner that the resulting system could be competitive in relation to the open systems, which have a predominant share in the market.

2 General characteristic of biological material

Algae form the group of photosynthetic microorganisms, as they possess the ability to convert solar energy into chemical one [29-30]. They form a source of valuable substances, i.e. proteins, lipids, hydrocarbons, vitamins and microelements. Water forms the principal component of the biomass, as it forms 75–90% of the harvested mass before processing. The remaining ratio of the content is made by mineral salts and hydrocarbons (30–50%) and lipids (7–15%) of the dry mass [4, 9]. The specific composition of microalgae makes them applicable in various branches of the food, as well as beauty and pharmaceutical industries. The industrial processes can apply both microalgae (single cell algae – Fig. 1a) as well as multiple cell ones (Fig. 1b). The long list with the wide range of useful products based on algae, include: agar, alginate, pigments, biosorbents, anti-inflammatory, antifungal agents, beauty products and creams, as listed in the literature of the subject [9,4]. As a consequence of anaerobic digestion of biomass, it is possible to derive biomethane, and biodiesel on the basis of oil extracted from algae – as well as bioethanol – after saccharification and fermentation [2,7,24,28-29,31-32]. The capability to absorb volatile organic compounds, remove CO_2, treat wastewater has led to the use of algae in the controlled ecological life support system (CELSS) in conjunction with photosynthesizing bacteria and higher plants, as this can solve the problem of oxygen supply to astronauts and CO_2 removal during long-term space missions.

The growth of algae is determined by a number of factors, which are defined as abiotic, biotic, and process related. Abiotic factors include the light, as the growth of biomass requires both light exposition over a given time, its adequate intensity, temperature, concentration of nutrients, O_2 and CO_2 content, pH value, salinity and presence of toxic chemicals [28]. Biotic factors include the presence of pathogens (bacteria, fungi, viruses) and the mutual effect of other algae strains [34]. An important group of parameters affecting the growth of algae is imposed by such process parameters as: intensity of mixing, biomass concentration and the related frequency of algae harvesting.

a)



b)

Fig. 1. Algae with potential application in industry:
a) *Chlorella vulgaris* – single-cell alga; b) *Laminaria japonica* – multi-cellular algae [33].

An indispensable component of each biomass growth system is associated with the medium in which the organisms develop and reproduce. Water forms the basic component of the algal cultivation system. The medium used for algae cultivation needs to include not only a source of carbon but also a variety of other necessary mineral compounds, which are parts of the algal cells. On the basis of an approximate molecular formula of algae biomass, Chisti [28] listed the basic elements forming this biomass: nitrogen (N), phosphorus (P), iron (Fe) and in some cases also silicon (Si). Apart from these elements, the medium contained in the water should include manganese (Mg), calcium (Ca) and sulfur (S) [8,28]. In general, the cost of cultivation is small when compared with the post-production procedures, such as draining and drying of biomass. In the closed system, supplementation of the medium is used, which means that nutrients are added during the course of the cultivation. Carbon forms the prevalent component in the photosynthetic cells of microalgae, as it forms around 50% of the dry mass in the content. The effective algal biomass cultivation systems include a constant supply of CO_2 as the principal source of carbon [28]. Experimental data indicates the increase of carbon assimilation coefficient along with the rise in the CO_2 concentration in the atmospheric air [35]. The generation of 100 tonnes of algae uses 183 tonnes of CO_2 supply [36].

An important aspect of the cultivation is associated with agitation of microalgal suspension, which prevents the sedimentation of cells, positively affects the distribution of CO_2, O_2 and nutrients contained in the liquid. In addition, this process can provide similar access to light by transferring cells from dark areas to light ones and promoting heat exchange [2,32,37-38]. An important exploitation aspect of microalgae cultivation is related to the ensuring and keeping the necessary temperature. Beside light intensity, temperature forms one of the parameters which can promote or limited the growth of the algae both in the closed and open cultivation system. Both the deficiency as well as surplus of heat can slow down the growth of microalgae, and in extreme case, the growth can be stopped. There are several ways in which energy can be fed into the system – by pumping air or exhaust gases rich in CO_2, agitation of algae as well as use of external heat source. Some cultivation systems require cooling during the day, e.g. by application of heat exchangers and cooling coils submerged in the deaeration chamber, as it is the case in the tubular photobioreactor design. In the dry climate, it is also possible to apply evaporation cooling involving water atomization along the surface of photobioreactor tubes. Water is used to naturally extract heat from the tube surface and results in the temperature decrease of the medium. Large photobioreactors can be located in greenhouses, thus securing the maintenance of a controlled temperature [28].

We can stress at this point that all of the above parameters, i.e. photobioreactor size, its design, light intensity and source, depth of light penetration, technique of feeding CO_2 and agitation mechanism can be adjusted to ensure the maximum growth of algae [39].

3 Design and operation parameters of photobioreactors

One of the basic parameters which considerably affects the design of a photobioreactor is associated with need to maintain adequate light penetration into the algal culture inside the reactor. This can be achieved by ensuring the considerable ratio of its surface area to its volume [9,10]. Smaller light intensity does not need to mean lower algae production efficiency because the majority of algae species can adapt to the low light penetration and its surplus (i.e. amount above the needs of photosynthesis) is emitted by microorganisms in the form of fluorescent light and dissipated in the form of heat [40]. This fact should be accounted for during the design stage and operation of photobioreactors to the biological processes occurring inside them. These, in turn, affect the efficiency of the photosynthesis and, consequently, the productivity of the biomass and its quality [39,41]. In particular, two papers explored the subject of effectiveness of light exposition [42-43]. These studies report that the maximum efficiency of solar light conversion into biomass on the way of oxygenic photosynthesis can be equal to 8–9%; however, with a note that the authors suggest the adoption of a lower value, i.e. 4.5% as a more realistic figure. Other aspects, which need to be taken into account during the design of photobioreactors include the potential of cultivating various algal species, possibility of maintaining biological purity of the species, keeping fast CO_2 and O_2 transfer, ability to clean and keep the environment sterile, keeping and controlling the important exploitation parameters from the biotechnology point (pH, temperature, medium composition, gas concentration) and adequate operation without the formation of foam [8,10].

A number of various photobioreactor designs were developed with a purpose of cultivating different algae meeting the requirements listed above. In general, such apparatus can be divided into tubular, flat, fermenter and hybrid reactors. The first of the designs was designed particularly with the purpose of effective absorption of solar radiation, whereas the two further designs require the use of artificial light (from an external or internal source) [9]. Fig. 2 contains a diagram with an original classification of reactors designed for algal cultivation with the shape as the criterion for classification. The further part of this work contains a detailed characteristic of photobioreactors along with the list of their advantages and drawbacks as well as the range for their practical applications.

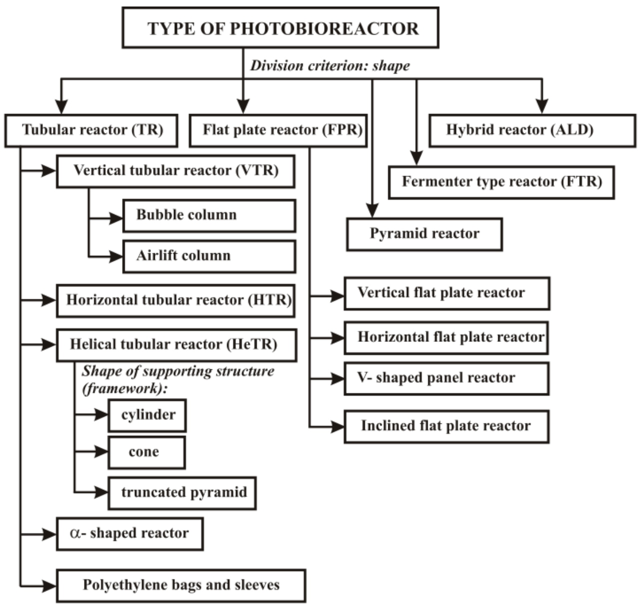


Fig. 2. Designs of bioreactors adapted to algal cultivation.

3.1 Tubular photobioreactors

Tubular reactors include three basic configurations, i.e. simple vertical column bioreactors with bubble and airlift columns, vertical tubular reactors and spiral reactors. This category of bioreactors also includes photobioractors with inclined pipes under a given angle in relation to the ground and the reactors in the shape of the letter α [44] as well as bag and sleeve photobioreactors made of polyethylene installed on arrangements based on supporting structures.

The first type of reactors, i.e. airlift and bubble columns are built in the form of vertical, transparent tubes, through which light penetrates the inside of the reactors thus ensuring an adequate level of light penetration into the cultivation.

3.1.1 Bubble columns

Bubble columns are cylinder-shaped vessels with the internal diameter often exceeding 20 cm, in which the geometrical condition H>2D is fulfilled (Fig. 3a). Usually this shape factor, i.e. the ratio of the height to the diameter is in the range from 4–8, as such a design can ensure an optimum relation of the reactor's surface to its volume. As they are produced from common materials, such designs are cheap and are suitable for both outdoor and indoor algae cultivation. In addition, there are no moving mechanical parts in the design, which could potentially cause shear stresses and promote cell degradation. Besides, satisfactory heat and mass exchange is maintained and uniform environment for cultivation is promoted accompanied with effective O_2 release. In such reactors, the agitation of the suspension is realized by the presence of the gas phase, which is introduced into the culture in the form of small bubbles formed by a distributor located in the lower part of the column, which guarantees a sufficiently long duration of the contact between the algae and the gas phase.

For the case of tall columns, perforated plates are applied to gain a greater dispersion of the gas phase [10] or rubber membrane diffusers [45]. The mixing process achieved in this manner leads to a uniform distribution of algal cells in the reactor volume and the uniform access of algae to CO_2 as well as enables the successful removal of oxygen production by the algae during photosynthesis [46]. The effectiveness of photosynthesis can be increased by a greater rate of gas feed; thus the duration of the light and dark cycles is reduced by keeping the algae in the sunny and shady areas of the photobioreactor for a shorter period.

The list of the drawbacks of this solutions include the susceptibility to formation of biofilm on the column walls, which limits light penetration inside the apparatus and reduces the effectiveness of photosynthesis as well as the need to set aside large plots of land for leading high-efficiency installation. The remaining limitations primarily concern outdoor cultivations. These include difficulties in the control of the temperature of the culture and the occurrence of photoinhibition phenomenon, which involves stopping of algae growth as a result of too large light exposition that exceeds the light saturation constant [28, 47]. The regulation of cultivation temperature can apply thermostats, but this leads to a considerable cost increase.

3.1.2 Airlift photobioreactors

Airlift photobioreactors are formed by mutually interconnected cylinder-shaped vessels with two separate zones, i.e. riser and downcomer zones (Fig. 3b). There are three design solutions of such apparatus, i.e. one with internal circulation (with an overflow pipe inside), cylinder with a partition to separate the riser and

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downcomer zone and a configuration with external circulation. In this type of apparatus, liquid circulation is obtained as a result of differences in the fluid density in the particular parts of the apparatus. In the risen zone, where gas feed is provided, the density of the mixture (i.e. suspension with dissipated gas phase) is lower than the one in the downcomer zone. As a consequence, the suspension rises in the aeration zone and it flows down in the downcomer zone. There are also lesser known designs, including rectangular airlift photobioreactors, which demonstrate better agitation characteristics and better efficiency of photosynthesis. However, they are unsuitable for large-scale cultivation [10].

The principal factor responsible for cost generated in bubble and airlift columns is associated with the cost of gas that needs to be supplied and this considerably affects the profitability of algae production. A comparison of the cultivation cost of *Porphyridium* algae in bubble and airlift columns is reported by Merchuk et al. [48]. As a result of adding a promoter that causes spiral gas flow, the cost of gas used to produce 1 kg of biomass dropped by 50% in relation to the cost in the bubble column on condition that the same specific algae growth rate is maintained. This study also demonstrated that in bubble and airlift photobioreactors with the dimension of up to 0.19 m, it is possible to gain a final biomass concentration and an adequate growth rate comparable with tubular photobioreactors with a narrow design.

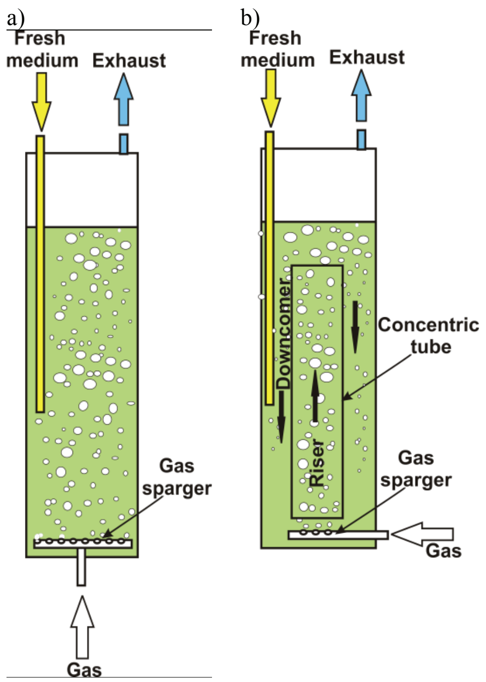

Fig. 3. Column type photobioreactor**:** a) bubble column, b) internal loop airlift.

3.1.3 Polyethylene bags and sleeves

Due to their low cost, transparency and sterility at the time of starting cultivation (high temperature of film extrusion), photobioreactors in the form of polyethylene bags are often applied (Fig. 4). These photobioreactors take the form of vertical bags, hanging individually or in the form of parallel series of bags mounted on a support (rack). A circulation pump is used to drive the flow of liquid through the particular bags, feed air inside the bag and provide medium. Such systems are characterized by good surface area to volume ratio. Cohen et al. [49] reported results with regard to bags with the capacity of 25 l (32x250 cm) to cultivate *Porphyridium* algae strain in which three times greater concentration of cells was obtained in relation to the typical value recorded in cultivation ponds. For the case of the use of *Spirulina*, the maximum productivity of such systems can be equal to 0.6 $g \cdot l^{-1} \cdot t^{-1}$ under the assumption of a reactor capacity of 100 ton (with the necessary surface for the cultivation of 1200 m^2). Tredici and Rodolfi [50] developed the idea of a photobioreactor in the form of a transparent elastic bag (foil) contained in a stiff, metal frame. In turn, authors in [31] applied polyethylene sleeves with a bubble column for cultivation of *Scenedesmus obliquus* microalgae. They discussed the advantages resulting from the outdoor cultivation and indicated the applicability of this bioreactor design for commercial production of algae in the context of gaining biomass designated for use in biofuels. Although the cultivation in such systems is easy and therefore quite common (also for multiplication of strains, there are considerable limitations resulting from the brittleness and low strength of the material exploited over prolonged periods of time. In addition, an increase in the volume of the algae cultivation systems is often associated with a drop in the efficiency of biomass production [9].

Fig. 4. Polyethylene sleeves.

3.1.4 Tubular photobioreactors

Tubular photobioreactors are formed by series of parallel tube sections, which can be joined in loops or systems inclined at a given angle against the ground (Fig. 5a-b). They are particularly suitable for the case of continuous outdoor cultivation, where the possibility of arranging reactors under an angle to the sun (in the north-south or east-west arrangement) provides adequate capture of solar radiation and ensures a high coefficient of light conversion. Such systems are designed to contain large volumes of cultivation media (with the tube diameter 10–60 mm, and a length of several hundred meters) since

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they are not susceptible to microbiological contamination [40]. In general, we can distinguish two types of tube arrangement in vertical tubular photobioreactors, i.e. solar tubes installed in parallel to one another low above the ground and tube installed on top of one another supported on a horizontal ladder-shaped rack. The purpose of this design is to increase the number of tubes per surface area of the available ground. The tubes are coupled with a gas exchange system (degasifying column) and a heat exchange system. The role of degasifying column is concerned with removal of O_2 produced during photosynthesis as the factor responsible for photooxidization [51]. The internal diameter of the pipe of the solar collector is limited and should be equal to up to 0.1 m due to the difficulties in the sun penetration into the deeper layers of the high-density algae suspension, which is necessary to gain a considerable biomass growth [28].

a)

b)

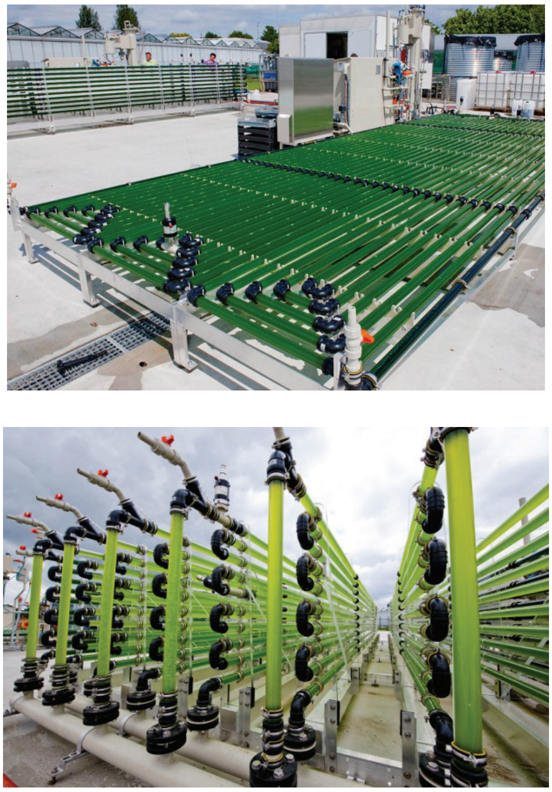

Fig. 5. Design of tubular reactor [9]: a) horizontal b) stacked tubular algae reactor consisting of several connected loops (Algae PARC Wageningen University).

The algal culture is circulated from a vessel (degasifying column) into the solar panel (which receives sunlight) and returned into it, which prevents the photoinhibition phenomenon. On the basis of data by Chisti [28], the maximum rate of oxygen generated in photosynthesis in a tubular photobioreactor can even exceed 10 $g \cdot m^{-3} \cdot min^{-1}$ in the conditions of high insolation. The dissolved oxygen cannot be removed directly from the tube only in the degasification column, which means that the length of a straight pipe section in such installations cannot exceed 80 m. The ground under the sun collector is painted white or covered with a sheet of white material in order to increase light reflection and that is how the total light flux received by the tubes can be increased [7]. A solution involving artificial lighting (fluorescent lamps, light emitted by LED diodes) of the tubular photobioreactors is technically viable but this is an expensive option compared to the natural light, hence, thus it is mainly used for biomass production on a large scale with regard to top-of-the-range products [52]. The adverse phenomenon of algae sedimentation is prevented by maintaining turbulent flow of the algal suspension induced by a mechanical pump or by application of airlift devices. It is also possible to realize the mixing by the application of static agitators, which however reduce the light penetration into reactor. The relatively high linear velocities of the fluid in the range of 0.20–0.50 $m \cdot s^{-1}$ require large expenditure associated with its pumping and this value can be in the range 2000 $W \cdot m^{-3}$ (for flat panel reactors and bubble column ~ 50 $W \cdot m^{-3}$). The turbulent flow of the thick algae suspension from the dark to the light zones effectively reduces the duration of its stay in the particular zones, and reduces the occurrence of photoinhibition, which is adverse for algal growth [10].

In the systems without temperature control, large volumes of heat can be generated (with the fluctuations in the temperature in the range of up to 20°C during the day). For the purpose of the reduction of this exploitation problems, reactors are often located indoors (in greenhouses) made of metal, glass or plexiglas. There are also available options of providing shadow to tubes by using dark plastic covering, tube overlapping, spraying tube surfaces with water and an option of tube submersion in a water tank. The latter solutions are effective though expensive, since the maintenance of a low temperature of the medium requires the use of considerable amounts of water [9]. A simple way of increasing the scale of the bioreactor processes is associated with installing a new set of tubes to the already existing installation while maintaining an adequate linear velocity of the medium and gas exchange at a given level. The only problem can be related with the size of plot needed for this installation. Industrial production with the capacity of 5000–10000 liters in systems with high light concentration could only be realized by installing large tube numbers arranged in a vertical system, which is questionable from the cost-effectiveness angle. The greatest bioreactor in the world (serpentine reactor) with vertical arrangement of horizontally running tubes consists of 20 independent modules with the total length of 500 km and a capacity of 700 m^3 is designed for cultivation of *Chlorella* microalgae strain on an industrial scale (with the annual output of 130–150 t of dry mass per year) and is situated in Klötze (Saxon-Anhalt, Germany). The required cultivation temperature is secured by enclosed space in a greenhouse with the surface area of 1.2 ha and adequate heating and cooling systems [7,40]. The highest productivity equal to 25 $g \cdot m^{-2} \cdot d^{-1}$ was, however, obtained in a reactor with a relatively small capacity of around 10 m^3 [8]. For the case of *Spirulina* production in a tubular reactor with the capacity of 100 ton (with the required plot of land for cultivation of 1200 m^2), the maximum

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productivity is 0.8 $g \cdot l^{-1} \cdot t^{-1}$. Due to the problems with light penetration, these bioreactors are designed for tube diameters not exceeding 30 cm.

Another stage in the development of algae production systems was associated with the design of tubular bioreactors with a set of parallel tubes arranged under the angle of 5–7^{o} in relation to the horizontal plane [9]. These tubes are made from flexible PVC (with a length of 6.4 m, diameter of 43 mm, and a thickness of 0.15 mm) and they are coupled by collectors made of PVC. The top collector plays the role of a degasifying column, whereas the lower one includes a perforated tube and is applied as a gas distributor to feed the particular tubes in the system. The temperature of the cultivation is regulated automatically by opening a valve and launching the spray. The largest experimentally examined bioreactors had a capacity of 4000 l and consisted of a set of 8 parallel tubes with the length of 44 meters. The mean productivity during the cultivation of Nannochloropsis strain was at a level of 0.7 $g \cdot l^{-1} \cdot d^{-1}$. The advantages of such photobioreactors are basically the same as other tubular designs, yet, the drawbacks are associated with insufficient gas transfer and no possibility of a satisfactory temperature control.

3.1.5 Helical tubular photobioreactors

Other solutions of bioreactor design are based on the potential application of flexible, transparent tubes with the internal diameters from 2.4 to 5 cm made of polyethylene, which are spirally wound on a cylinder-shaped (e.g. Biocoil), truncated pyramid or truncated cone shaped support structure. Several systems involving parallel running tubes are coupled by collectors with a system for liquid pumping (i.e. a pump or airlift layout). The use of centrifugal pump for microorganism pumping could form an element which excludes the possibility of cultivating selected algae species in a spiral photobioreactor, in particular the ones that are susceptible to shear forces, as they can lead to destruction of algal cells.

A bioreactor could also be equipped with a gas exchange system [34]. This type of photobioreactor is considered as one of the most effective designs, dedicated to the cultivation of small volume of microalgal suspension, i.e. for multiplication of strains for further use in larger tubular reactors [28]. The principal disadvantage of this design is related to the possibility of the occurrence of the fouling phenomenon, which involves tubes blocking as a result of the excessive growth of algal biofilm. The ways of reducing algal biofilm thickness include purposeful induction of air plugs in the tube, circulation of balls matching the internal diameter of the pipe in size, inducing flow of very turbulent fluid, as well as flow of sand and coarse particles suspended in the liquid with abrasive characteristics. In turn, the advantages of this design include the good relations between the energy consumption and the effectiveness of photosynthesis, uniform mixing, effective CO_2 from the gas to the liquid phase, smaller degree of algae exposition to mechanical stress and the relatively small requirements with regard to surface needed for the installation in relation to the relatively large volume of the cultivation medium [9]. In addition, there is a possibility of applying artificial light, whose source is located inside the apparatus, as it enables the effective control of light absorption by the culture to be performed. This measure can compensate for the not necessarily good adjustment of the apparatus in relation to the sun. The scale-up of the system is easy and involved an increase of the number of the parallel tube layer in a spiral.

In a spiral bioreactor in the truncated cone shape, it is possible to utilize light and solar radiation falling on the tube surface in a more effective manner. This shape provides a better spatial distribution of light and its absorption by microorganisms. The main disadvantage is associated with difficulties in rescaling, as the geometrical parameters (angle, height) are strictly defined. The only way of achieving a high pace of photosynthesis is related to the increase in the number of coupled apparatus, which contributes to the energy losses in the complex of network with liquid flow. The productivity in such complex system is also considerably lower calculated per size of the necessary plot of land.

3.2 Plate (panel) photobioreactors

Bioreactors in the shape of flat panels form some of the designs with the best parameters in terms of strength (Fig. 6).

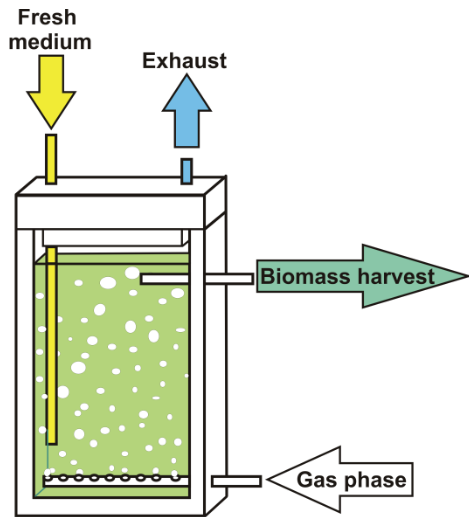

Fig. 6. Plate photobioreactor for algae cultivation.

They are formed by two adhesive sheets of transparent material (glass, plexiglas, polycarbonate) with the length of the route of light penetrating through it (d) in the range of a few to 70 mm. The large surface of the exposition offers high efficiency of photosynthesis [2]. The geometry of a single flat panel provides a high ratio of the reactor surface to its volume, which results in a higher efficiency of biomass production [35]. In accordance with the current state-of-the-art in the area, it is beneficial to maintain this ratio around 400 $m^2 \cdot m^{-3}$. In the cultivations, in which this condition is fulfilled, the

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specific efficiency of biomass production is gained in a small volume of the cultivation medium and in the conditions of low energy expenditure for mixture agitation. In this bioreactor design, the parameter defining the ratio of their surface to the area of the plot which is occupied by the cultivation, should be equal to at least 10. The optimum value of this parameter is obviously relative to the type of the microalgae strain and the region, in which the apparatus is located [35].
The agitation is realized by use of gas phase (air) circulating along a perforated tube located in the bottom part of the apparatus (1 liter of air per 1 liter of reactor volume per 1 minute) or by application of a rotating mechanical module [19]. Some algae species in this type of reactor can be exposed to hydro-mechanical stress and form biofilm on the apparatus walls. There are suggestions that the plates should be arranged in a stack, perpendicular to the angle of the light falling on the reactor. This procedure is intended to identify the areas with various intensity of light penetration in the apparatus, which is desirable for the case of microalgae cultivation with various levels of photoacclimatization or intention of synthesizing specific products that can only be formed in the conditions of considerable insolation.
This apparatus are relatively cheap and easy to clean but difficulties can arise in connection with temperature maintenance. Large-scale cultivation can require the use of numerous modules and installation of support structures.

3.3 Fermenter type photobioreactors

Tank photobioreactors (fermenters), including commonly designs with a circular cross-section (Fig. 7) (sometimes with a rectangular as well), are made of steel, glass and organic glass applied predominantly in cultivations on a laboratory scale.

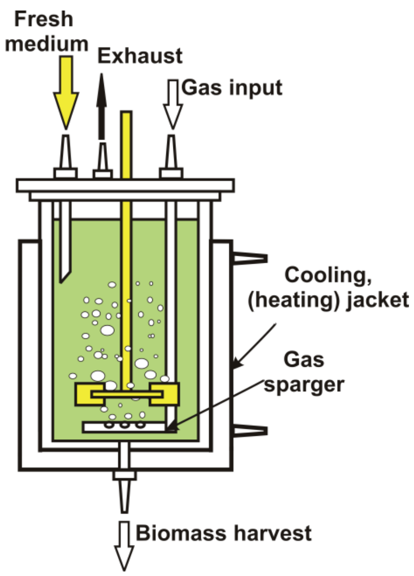

Fig. 7. Fermenter type photobioreactor.

They are included in the conventional system family, in which the medium is agitated mechanically by use of stirrers with a variable shape and size. Air feed together with CO_2 is supplied through the agitation system or directly under it. Beside natural light, it is possible to apply artificial lighting (fluorescent lamps, optic fibers), as this can ensure a uniform distribution of the rays of light. As a consequence of the insignificant ratio of the reactor surface to its volume (which is characteristic for this design), the effectiveness of light absorption is also small. The cultivation can be performed periodically, as well as in a semi-continuous and continuous manner. The complete control of the process parameters coupled with the many years' experience in biotechnology processes and running them on a various scale in the food and pharmaceutical industries also can provide the procedure realized in an axenix culture (i.e. free of undesired organisms). These microorganisms can be maintained in a reactor for a longer period, which plays a key role in the production of selected high-value metabolites [9]. The productivity of the biomass in such systems is very small and typically equal to 30–50 $mg \cdot l^{-1} \cdot d^{-1}$; therefore, the design of this reactor is continuously enhanced with the purpose of improving the efficiency of algal biomass growth.

3.4 Hybrid photobioreactors

Hybrid systems of algae cultivation involve the integration of various phases of microalgae growth in a single two-stage system. The initial part of algae growth takes place in a closed system (i.e. photobioreactor), whereas the subsequent ones in the open system. Hence, the hybrid systems include components and design solutions that are characteristic of the various cultivation systems, i.e. open and closed ones. The first phase of the cultivation is realized in a photobioreactor, which is meant is minimize the hazard associated which the contamination of the cultivation by foreign organisms while the beneficial conditions for cell multiplication are maintained. The second stage of production is designed to expose the cells to the stress of nutrients, which should initiate the synthesis of desired metabolites and lipid products and it is realized in cultivation ponds. Such system can include the production of oil and astaxanthin by *Haematococcus pluvialis*. Huntley and Redalje [53] reported that the mean amount of oil that can be gained from algae in this manner was equal to above 10 $tonnes \cdot ha^{-1} \cdot year^{-1}$ and the maximum was even 24 $tonnes \cdot ha^{-1} \cdot year^{-1}$.

3.5. Pyramid photobioreactors

Pyramid photobioreactors are some of the newest systems of algal cultivation, as they are completely computerized and automated. The fluid mixing is realized by an airlift system. The maximum production of *Spirulina* is equal to 1.45 $g \cdot l^{-1} \cdot t^{-1}$ and this value is over 4 greater in relation to the productivity in the open systems and it well exceeds the value gained in the tubular photobioreactors. The advantages of this system include the small area of plot required, i.e. around 60 m^2 for the cultivation medium with the mass of 100 tonnes. However, such designs are still mainly at an

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experimental stage. For the purpose of indicating the potential applicability of selected types of photobioreactors, Table 1 contains a brief characteristic of each of the designs, which includes the list of their advantages and drawbacks. The most effective designs of closed systems of photobioreactors utilized nowadays include bioreactors in the form of flat panels, tubular reactors and bubble columns [9, 52-54]. The popularity of bubble columns stems from their low maintenance cost, beneficial ratio between the surface of the reactor and its volume, as well as lack of moving parts and effective O_2 removal. In outdoor cultivations, the most effective systems involve the use of horizontal tubular reactors, as this design promotes CO_2 diffusion and the use of solar radiation is maximized, which can provide better productivity in relation to flat reactors. Finally, adequately modified flat photobioreactors are capable of offering maximum productivity even in the conditions of smaller light intensity.

Table 1. Comparison of advantages and drawbacks corresponding to selected types of photobioreactors.

Column photobioreactors (bubble and airlift column)
Advantages: • good biomass growth, high efficiency of photosynthesis, high potential of scalability, limited photoinhibition and photooxidization • cheap, compact and easy to maintain • potential of exposition to alternating dark and light cycles • small prerequisites of space demanded for cultivation • suitable for outdoor cultivation • low energy use • suitability for algae immobilization
Drawbacks: • small area of light exposition that is additionally reduced with the increase of column diameter • low ratio of reactor surface to its volume • possibility of biofilm formation on reactor walls
Applicability: Not suitable for algae cultivation with a low specific weight, e.g. strains containing large volume of lipids, since the cells of these algae are highly susceptible to flotation.
Flat (panel) photobioreactors
Advantages: • large surface of exposition to light • high ratio of surface to volume • suitable for outdoor cultivation • high productivity of biomass • ability to maintain uniform access to light across entire volume of cultivation • relatively cheap • easy to build, maintain, clean and operation • high efficiency of photosynthesis • suitability for algae immobilization • small concentration of dissolved oxygen
Drawbacks: • any increase of production scale requires the use of numerous modules and support structure • difficulties in control of cultivation temperature • risk of fouling • potential for occurrence of hydrodynamic stress in some algae species
Applicability: Production of algal strains with a high lipid content at limited access to nutrients.

Table 1 (cont.)

Tubular photobioreactors
Advantages: • large area of light exposition • suitability for outdoor cultivation • good productivity of biomass • relatively low cost of build
Drawbacks: • considerable requirements in terms of plot area for installation • possible fluctuations in pH, concentration of dissolved O_2 and CO_2 along the tube length (risk of photoinhibition) • risk of biofilm accumulation on tube walls • poor mass transfer
Applicability: Industrial production of valuable dyes, astaxanthin and for production of *Haematococcus*, *Nannochloropsis, Chlorella* strains.
Fermenter type photobioreactors
Advntages: • possibility of running axenic cultivation • control of all process parameters
Drawbacks: • low ratio of surface to volume • low efficiency of light absorption • low productivity
Applicability: Cultivation of marine algal species, i.e. *Chondrus crispus*, *Gracilari*, processes of biological wastewater treatment, production of high-value metabolites.

4 Conclusions

Concerns about global warming, increasing CO_2 emission and environmental pollution caused by fossil fuels, combined with their depletion and energy security are important factors in the development of alternative energy sources that is renewable, clean and environment friendly. In this context, algae biomass is becoming important potential resource for renewable energy production. Despite the progress that has been made in the recent years in the field of bioengineering and biotechnology, which promotes the improvement of the efficiency of algal growth in photobioreactors, open systems are dominant in algae cultivation on the industrial scale. This is principally due to a number of unresolved technical problems, high cost of investment and production in photobioreactors. The basic advantages listed in this paper associated with the use of photobioreactors on an industrial scale include the possibility of gaining high quality biomass, in which the volume of production often exceeds the productivity of the open system by a few times, reduction of water use by several orders of magnitude, direct exposition of algae to sunlight and control of CO_2 concentration. The designs of photobioreactors (e.g. tubular, panel) and optimization of operation parameters are continuously improved with the purpose of gaining maximum efficiency of biomass production while high efficiency of the use of supplied resources is concurrently preserved (e.g. water, energy, nutrients). These processes are optimized continuously in terms of sustainability and environmental friendliness.

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