science • technique

Overview of photobioreactors for the production of biodiesel

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Introduction

Microalgae are the longest living autotrophic taxon in the world [1]. Algae are tissueless organisms, protozoans or simple multicellular organisms. Among them are both prokaryotic microalgae (cyanobacteria, otherwise known as blue-green algae), as well as, eukaryotes, eg. green algae (*Chloroxybacteria*), red algae (*Rhodophyta*) and diatoms (*Bacillariophta*). Algae can reproduce sexually or asexually [2÷4]. They synthesize three main biochemical compounds and namely: carbohydrates, proteins and lipids (natural oils). Thanks to their high growth ratio they are widely recognized for synthesizing and accumulating a significantly larger amount of lipids than terrestrial plants [1]. They are considered to be the most resistant organisms on Earth, capable of growth under varied conditions. They can be found in humid areas and on water surfaces. They inhabit both fresh, as well as, extremely saline waters and practically each environment with sufficient access to light. They are also widely spread on land. The only thing what they have in common with higher plants is the presence of chlorophyll and the photosynthetic capacity.

Use of algae

Algae have a variety of applications in the production of pharmaceuticals (antibiotics, vitamins, functional food, algaecides), dyes, proteins and as a water purifying agent [5÷8].

Illustration 1 shows the process of breeding algae beginning from the intake of light energy and carbon fixation and ending with the intended practical use of products which originated from biomass [9].

Algae in the production of biodiesel

Comparing algae with the raw materials of the first and second generation, they can produce more energy per hectare [10]. The biodiesel production technology has been known for more than 50 years [11]. From 1 hectare it is possible to obtain from 10 to even 100 times more oil than in case of cultivating oil plants. Additionally, the life cycles of plants last from 3 months to 3 years and algae can start producing oil after only 3-5 days of breeding what enables daily harvesting. Algae can grow in salt water or on uncultivated land with water unfit for consumption where practically nothing else can be cultivated [9]. A large amount of lipids, proteins and carbohydrates are produced in a short time only thanks to access to light, sugars, CO_2, N, P and K. The mentioned products may be processed into biofuels or other useful organic compounds [9, 12]. The great advantage of algae as a raw material for the production of biodiesel lies in its fast growth and high oil content in the cells (constituting 20-77% of dry mass) [11]. Additionally algae need less water for growth than terrestrial plants [13]. According to technical literature 1 kg of dry algae mass utilizes ca. 1.83 kg of CO_2, it may therefore be confidently stated that algae help remove CO_2 from the atmosphere and thus can be used to improve air quality [11]. Another advantage for the environment is also the fact that algae during the breeding process do not require any herbicides or pesticides. Proteins and the residual biomass after the oil extraction can be used as fertilizers or may undergo fermentation for the production of bioethanol or bioethane. The adequate biomass composition of algae may also be changed by using various breeding conditions [13].

The basic production of biodiesel from algae consists of three stages: cell culture, separation (detachment) from their culture medium and the extraction of lipids [7]. The oil content in the algae cells depends on their species. There are more than 50 000 living algae species, but not all of them are suitable for the production of biodiesel. This is mainly due to physiological processes and breeding conditions [14]. The most promising groups of algae in the production of biodiesel are green algae, diatoma and cyanobacteria [15].

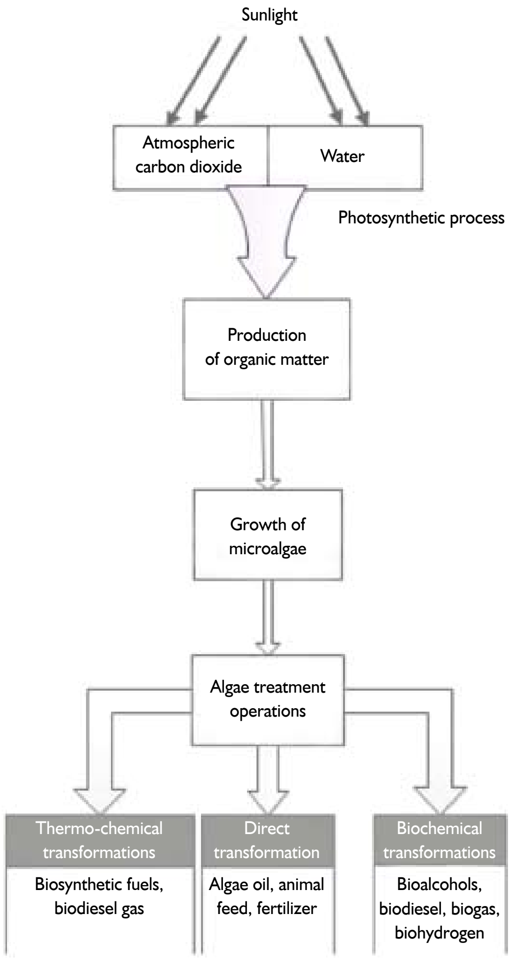

Illustration 1. Algae culticvation

Biomass production – breeding conditions of algae

When considering the use of algae for the production of biodiesel it is important to define the impact of breeding parameters and the option to handle them in order to obtain the maximum possible

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biomass yield. This is the only way to entirely control the population of microalgae, even when breeding on a large scale. Both abiotic, biotic components, as well as, process factors have an impact on the growth of algae. The abiotic components include light (both time and intensity of exposure are important here), temperature, concentration of nutritional substances, O_2, CO_2, pH, salinity and presence of toxic chemicals. Biotic components mainly contain pathogens (bacteria, fungi, viruses) and interact with other species of algae. The process factors include mixing, biomass concentration, depth and frequency of harvesting algae.

The culture medium should contain inorganic compounds which are found in algae cells. The most important elements in this field are: nitrogen (N), phosphorus (P), iron (Fe) and in some cases also silicon (Si). Besides these components, magnesium (Mg), calcium (Ca) and sulphur (S) should also be supplied. In most cases seawater is used for breeding marine algae enriched with commercial nitrogen and phosphorus fertilizers and a few chosen microelements [11]. An important component of each nutrient is water required by the photosynthetic organisms to produce biomass. This is a factor which cannot be substituted by anything else. The culture media do not generally constitute high costs. When choosing the adequate nutrient it is necessary to answer the question how many nutritional substances shall be sufficient to conduct the process not to incur additional costs connected with losses of the unused nutrient. In closed systems nutrients are added after the previous ones have run out.

Almost 50% of the dry mass of the microalgea biomass consists of carbon [16]. Usually the entire carbon is supplied in the form of carbon dioxide. 183 tonnes of CO_2 is used for the production of 100 t of the algae biomass. Carbon dioxide should be continuously supplied during the lighting of the culture. It is recommended to control the supply of carbon dioxide via the pH sensors what shall minimize the CO_2 losses and the pH value fluctuations [11].

The average quantity of solar radiation which reaches the earth each second amounts to ca. 1367 W/m^2, this is the so-called solar constant [17]. The proper quantity of radiation depends on the latitude, season and weather. The production of biomass on a large scale depends essentially upon continuous breeding with the use of solar light.

Temperature is – apart from the lighting conditions - the most restricting factor affecting the algae cultures both in closed, as well as, open systems. The impact of temperature under laboratory conditions for many species of algae has been quite well described. A lot of species easily tolerate temperatures about 15°C below their optimum, however a slight temperature increase of 2-4° C causes losses in algae cultures. On hot days in closed photobioreactors the temperature can even reach 55° C, that is why adequate cooling systems should be used [7].

All species of algae also have their own optimum salinity. The simplest way to control salinity is to add fresh water or the required amount of salt [7].

Mixing is a consecutive important factor that provides an even distribution of algae cells, heat, metabolites and facilitates the transfer of gases. Mixing is also recommended for the movement of cells from dark zones to light zones, especially in installations for producing algae on a large scale [7]. On the other hand, a high liquid viscosity and intensive mixing (mechanical mixing and aeration) may damage the cells [18]. The optimum mixing intensity depends on the strain and should be selected so as to avoid culture losses [19].

The possible contamination is also worth mentioning; the biological contamination may be caused by undesirable algae species, humus, yeasts, fungi and bacteria. It is, however, a problem which occurs more frequently in open cultivation systems than in photobioreactors.

Algae production systems

Algae may be cultivated in open systems (cultivation ponds) and in controlled closed systems called photobioreactors. Photobioreactors (PBR) are systems in which the cultivated culture is constrained by transparent material. These devices may have different dimensions and shapes; they can take the form of plastic bags, flat panels, tubes or fermenters. Vertical tubes are most popular: they are relatively easily maintainable, cheap and have a large area in relation to volume [20]. The biggest advantages of photobioreactors are: resistance against contamination, achieving high productivity per unit area and the possibility to easily control the cultivation parameters (pH, temperature, light intensity). It is also possible to prevent the growth of algae cells in them; they allow to save water and chemical agents [21]. Photobioreactors can be placed inside or outside buildings, sunlight or artificial light is used for lighting them or both options are used simultaneously. The use of optical fibres to transmit sunlight from the outside into the interior of the cultures found in buildings [22] which allows to reduce the energy input [1], is also an interesting topic. Both tungsten, as well as, fluorescent lighting can be the source of artificial light. It should also be emphasized that LED light (light emitting diodes) is increasingly used to grow algae, since it generates a small amount of heat, is energy-efficient and can emit light waves similar to PAR (photosynthetically active radiation). Current research shows that the length of the light wave has an enormous impact not only on the production of biomass and lipids, but also on their composition [23, 24].

The following issues should be considered in designing photobioreactors [2]:

- the reactor should allow to grow different algae species,
- the project must provide the same lighting on the whole area of cultivation and quick transfer of CO_2 and O_2,
- the reactor must be cleaned frequently and must undergo a sterilization process,
- photobioreactor must operate in such a manner so as to prevent the formation of foam.

Column photobioreactor

It is made of transparent (glass, plastic) vertical tubes so the light could freely penetrate its walls. It is necessary to install an aeration device in it allowing the incoming gas take the form of tiny air bubbles. Aeration by means of a mixture of gases ensures mixing, supply of CO_2 and allows to eliminate oxygen produced during photosynthesis [25]. The columns have a large exposure surface and they are cheap. You can grow algae in them outside. Depending on the aeration mode they are divided into two further described types. Their disadvantage is, among others, the susceptibility to the formation of biofilm and an indispensable large space. The additional limitation is the phenomenon of photoinhibition and the difficulty to control the temperature of growth [26] (it is possible to use thermostats, however they are difficult to use and they increase the costs of cultivation).

Bubble columns

They are cylindrical vessels of at least double the height of the diameter. Their advantages are: a low cost, a large surface/volume ratio, the absence of movable parts, a rather good transfer of heat and mass, a rather homogenous breeding environment and an efficient O_2 release. Both mixing, as well as, spreading CO_2 is possible thanks to gas bubbles which are released from the aeration device. By using such a system on a large scale, in particular with regard to high columns, perforated trays are used for separating the merged bubbles [2]. The columns are lit only from the outside.

The efficiency of photosynthesis can be increased by intensifying the flow of gas carried through the shorter light and dark cycles. Illustration 2 presents the diagram of the column with bubble aeration.

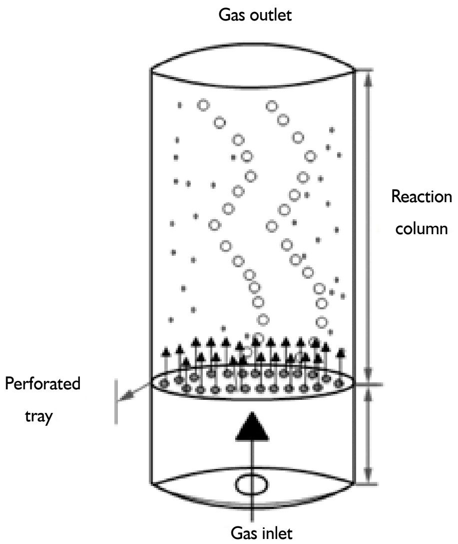

Illustration 2. Bubble column [27]

Airlift photobioreactors

They are comprised of vessels with two connected zones. The first zone is a pipe called the riser into which the mixture of gas is injected. The second zone is a downcomer to which gas is not supplied. Mixing takes places in the riser due to the passing gas bubbles (Illustration 3). Rectangular airlift photobioreactors are also known, they are characterized by a better mixing and provide high photosynthetic efficiency. However, they have not found any practical application due to difficulties in conducting the husbandry on a large scale [2]. The bubble systems and airlift bioreactors are not suitable for algae species with low specific weight, eg. strains producing a large amount of lipids, because these algae cells tend to float. Furthermore, mixing provided in such photobioreactors is insufficient [28].

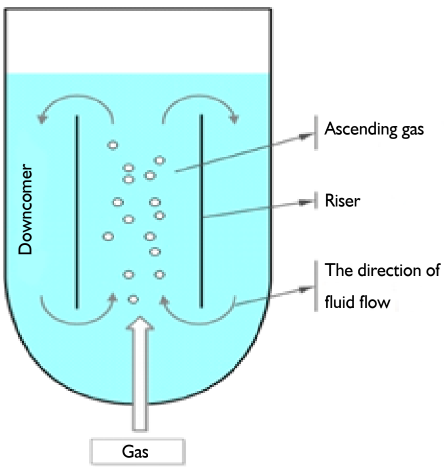

Illustration 3. Airlift column [29]

Panel photobioreactor

It is cubical in shape with the light path limited to the minimum. Panel photobioreactors are usually made of transparent materials allowing the maximum use of solar energy, such as glass, plexiglass, polycarbonates etc. They are characterized by a large surface area to volume ratio. Mixing can be carried out here by the airflow along the perforated tube (favourably 1 litre of air per each litre of reactor volume per 1 minute) or by rotating the module mechanically [1, 30]. Lighting a large surface area allows to achieve a high efficiency of photosysthesis [31]. The panel photobioreactor (Illustration 4) is characterized by a low oxygen level increase, it is also quite cheap and it is easy to clean. However, production on a larger scale requires the use of many modules and structures supporting them. It is worth mentioning that in such systems it is difficult to control the temperature, and some algae species may be exposed to hydrodynamic stress and the formation of biofilm. Panel photobioreactors are used to produce algae strains which accumulate lipids under conditions of limited access to nutrients [30].

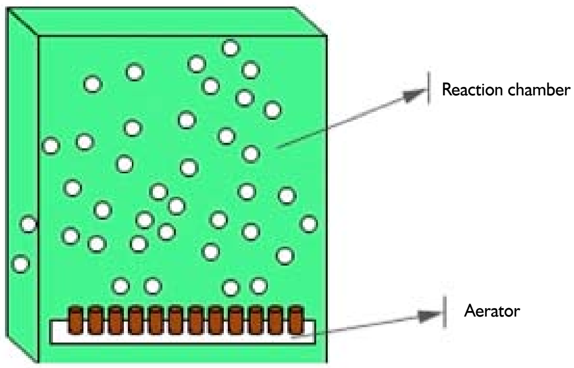

Illustration 4. Panel photobioreactor [32]

Tubular horizontal photobioreactor

This type of photobioreactor is made of a series of pipes placed horizontally (Illustration 5) which can be linked by loops or placed at a certain angle. Their shape is suitable especially for outside cultivation; the arrangement directed towards the sun results in a high light conversion ratio. The mixture of gas with CO_2 is injected into the tube linked with the gas exchange system which is called the degassing column. The task of this column is, among others, the removal of oxygen which originated during photosynthesis as it can cause photooxidation which reduces the efficiency of photosynthesis [33]. These systems can be cooled by sprinkling with water or placing tubes one on another; putting them into the pools with water temperature control or adjusting the temperature of the nutrient. A partial recirculation of the fluid is the other way of cooling.

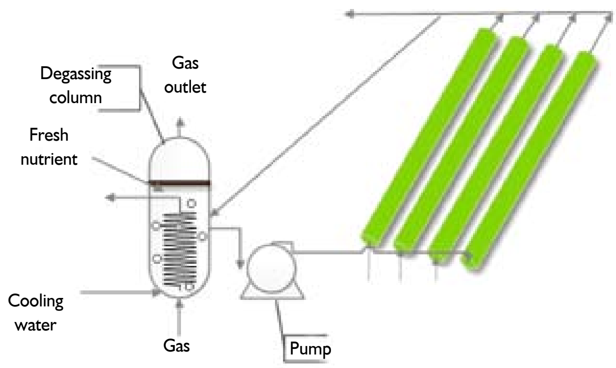

Illustration 5. Tubular horizontal photobioreactor [34]

The disadvantage of such a photobioreactor is a high energy consumption reaching even 2000W/m^3, whereas, in flat panel photobioreactors and the bubble aeration system the value amounts to 50W/m^3. Such an energy input is necessary to obtain high linear speed ensuring the achievement of turbulent conditions sufficient to obtain short light and dark cycles [2]. The system with slanting tubes is similar to the horizontal system; it differs in the sense that it is tilted towards the sun at an angle of a few degrees what helps to use sunlight more effectively. Such a system also allows to obtain a higher photosynthetic efficiency in relation to the flat panel photobioreactors. The tubular photobioreactors are used in industry for the production of valuable dyes, astaxanthin and for the production of *Haematococcus, Chlorella and Nannochloropsis algae* [30].

Spiral photobioreactor

It consists of folded flexible tubes of a small diameter with separate or attached degassing units. The tubes are transparent. The culture is moved to the degassing unit using the centrifugal pump. The disadvantage of this system is the fouling potential and the advantage is the maintenance of balance between consumed energy and photosynthetic efficiency, lower energy requirements and a smaller degree of the exposure of algae to mechanical stress. The whole system requires little space.

Tank photobioreactor

This is the most conventional system in which mechanical mixing is carried out via mixers of different sizes and shapes. Air enriched with CO_2 is introduced from the top of the tank. This type of bioreactor was transformed into a photobioreactor by using external lighting by means of fluorescent lamps or optical fibres. The disadvantage is a low surface/volume ratio. The tanks may also have a rectangular shape. Tanks of a rectangular cross-section contrary to the round ones do not require mixing devices, because mixing may be carried out via the adequate placement of gas distributors. Marine algae species such as *Chondrus crispus* and *Gracilari,* which are also used in the water treatment process by means of algae husbandry, are most commonly cultivated in tank photobioreactors [28].

Hybrid photobioreactor

A hybrid photobioreactor takes advantage of two different photobioreactors for obtaining better results; the options of using the chosen types of photobioreactors were described in Table 1.

Table 1

Comparison of disadvantages and advantages of chosen types of photobioreactors [4, 14]

Type of photobioreactor	Advantages	Disadvantages
Tubular	• high level of lighting suitable for outside cultivation • ensures high productivity of biomass	• requires large surface area • the process of photoinhibition often takes place in this type of photobioreactors • poor transfer of mass
Column	• quite good growth of biomass and high efficiency of photosynthesis, additionally it is easy to increase the scale • reduces photoinhibition and photooxidation processes • cheap, compact and easy to maintain • maintains gas balance well • enables to easily maintain dark and light cycles • requires a small surface area • suitable for outside cultivation	• small surface area of lighting • low surface area to volume ratio • possibility of forming sediment and overgrowths on the walls
Panel	• high level of lighting • high surface area to volume ratio • suitable for outside cultivation • ensures high productivity of biomass • guarantees the same access to light for the whole cultivation • low-cost accomplishment • easy to construct, maintain and clean and to grow algae • provides high efficiency of photosynthesis • suitable for immobilization of algae • provides low oxygen level increase	• it is difficult to increase the scale – cultivation at a bigger scale requires the use of many modules and supporting elements • it is difficult to control the temperature • algae cells adhere to the walls and form a biofilm • among some cultivated algae species hydrodynamic stress is intensified

Currently bubble column photobioreactors are most frequently used – due to low maintenance costs, a high surface/volume ratio, lack of movable elements, a relatively good transfer of mass and heat and efficient removal of O_2; flat panel photobioreactors, which after a suitable modification can ensure maximum productivity – even under conditions of reduced light intensity, are also popular. Tubular horizontal photobioreactors, which under external conditions ensure a better productivity than the flat panel reactors and perform well under laboratory conditions, are the most popular ones for external cultivation.

Summary

Microalgae have a higher growth rate than field crops. The annual quantity of produced algae oil per unit area is by 7-31 times bigger than for palm oil, the second raw material in terms of efficiency. Algae are an important source of biomass. Specific species can guarantee the production of different types of biofuels [35]. They can practically grow everywhere, even in sewage and salt water, they do not require fertile soils like oil plants. However, light and carbon dioxide are indispensable for growth.

It is possible that the biodiesel from algae will significantly supplement the liquid fuels obtained from crude oil. However, in order to make the process of production profitable, it should be improved and the genetic engineering measures and the improvement of the structure of photobioreactors should help achieve this goal. The photobioreactors according to their characteristics can be selected for specific algae cultures.

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KONKURSY, STYPENDIA, STAŻE

Kolejne stypendia na Start dla młodych badaczy

Stypendium w wysokości ponad 20 tys. PLN rocznie mogą otrzymać badacze przed 30 rokiem życia, w kolejnej edycji programu Start. Wnioski w programie realizowanym przez Fundację na rzecz Nauki Polskiej można składać do 31 października br. Głównym kryterium oceny kandydata jest jakość i oryginalność jego dotychczasowego dorobku naukowego oraz jego osiągnięcia badawcze. Program Start oferuje również dodatkowo stypendium wyjazdowe, które można przeznaczyć na kilkutygodniowy pobyt w naukowej instytucji zagranicznej. *(kk)*

(*http://naukawpolsce.pap.pl/, 24.09.2016*)

390 mln PLN dla naukowców w kolejnych konkursach Narodowego Centrum Nauk

W sumie 390 mln PLN mogą otrzymać naukowcy w kolejnych konkursach ogłoszonych przez Narodowe Centrum Nauki. W 12. edycji programów OPUS, PRELUDIUM i SONATA do zdobycia jest 330 mln PLN. W drugim konkursie BEETHOVEN na polsko-niemieckie projekty badawcze i ostatniej edycji konkursu POLONEZ mogą otrzymać po 30 mln PLN**.** POLONEZ to konkurs umożliwiający naukowcom z zagranicznych instytucji przyjazd do Polski na roczny lub dwuletni staż badawczy. Wnioskodawca musi mieć stopień doktora lub cztery lata doświadczenia badawczego w pełnym wymiarze czasu pracy, a także w ciągu ostatnich trzech lat nie powinien mieszkać, pracować lub studiować w Polsce dłużej niż 12 miesięcy. W drugiej edycji konkursu BEETHOVEN wprowadzono zmiany w stosunku do pierwszej edycji. Dotąd mogły w nim startować polsko-niemieckie zespoły badawcze, realizujące projekty z obszaru nauk humanistycznych, społecznych i o sztuce. Tym razem o finansowanie powalczą również przedstawiciele wybranych dyscyplin nauk ścisłych i technicznych. OPUS to najpopularniejszy konkurs NCN, skierowany do szerokiego grona odbiorców. Może w nim startować każdy badacz, niezależnie od stażu i stopnia naukowego. Uzyskane środki można przeznaczyć na stworzenie zespołu badawczego oraz zakup aparatury potrzebnej do realizacji badań. Dla badaczy rozpoczynających karierę naukową, którzy nie posiadają stopnia naukowego doktora, przeznaczony jest konkurs PRELUDIUM. Dla doktorantów jest to szansa na pierwsze samodzielne poprowadzenie projektu badawczego. SONATA jest również konkursem skierowanym do badaczy na początku kariery, jednak już nieco bardziej doświadczonych. O finansowanie mogą ubiegać się naukowcy ze stopniem naukowym doktora, którzy uzyskali go maksymalnie siedem lat przed złożeniem wniosku, a więc w latach 2009–2016.

Wnioski należy składać do 15 grudnia 2016 r. Wyniki konkursów OPUS, SONATA, PRELUDIUM zostaną ogłoszone do czerwca 2017 r., a konkursu POLONEZ – do maja 2017 r. Laureatów konkursu BEETHOVEN powinniśmy poznać w październiku 2017 r. *(kk)*

(*http://naukawpolsce.pap.pl/, 17.09.2016*)

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