Photobioreactors for Microalgal Biofuel Production

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1 Introduction

Biofuels have the potential to reduce the world's dependence on fossil fuels, but their production suffers from severe limitations like the requirement of vast areas of land and competition with food production (Brennan and Owende 2010; Mata et al. 2010). To be beneficial, biofuels must be produced without impacting on arable land or tropical rainforests and provide significant greenhouse-gas emissions savings compared to fossil fuels, characteristics which are expected in the so called "second generation biofuels", like cellulosic ethanol. Microalgae present several advantages over higher plants as source of second (or even third) generation biofuels. Microalgae cultivation shows less dependency on seasonal variations and requires less freshwater than conventional agriculture, making cultivation in arid regions possible (Mata et al. 2010; Tredici 2010; Wijffels and Barbosa 2010). Microalgae cultivation does not require herbicide or pesticide applications (Rodolfi et al. 2009; Williams et al. 2009). Microalgae can fix CO_2 efficiently from different sources, including industrial exhaust gases, and can use nutrients contained in wastewaters for their growth (Huntley and Redalje 2007; Wang et al. 2008; Brennan and Owende 2010). The combination of wastewater treatment, CO_2 fixation, and biofuel production through microalgae represents a promising alternative to current CO_2 mitigation strategies. Besides oil, microalgae can accumulate sugars, which can be fermented to produce bioethanol (Huesemann and Benemann 2009) and, above all, these microorganisms can synthesize many valuable co-products such as proteins, vitamins, hormones, polyunsaturated fatty acids that can be commercialized to integrate foods and feed (Brennan and Owende 2010; Tredici et al. 2009). Finally, the whole algal biomass or the residue after extraction of oil, carbohydrate or any other specific product can be anaerobically digested to obtain biogas or be gasified to produce syngas (Huesemann and Benemann 2009; Sialve et al. 2009; Mussgnug et al. 2010). The most important advantage of microalgae as source of biofuels is that they can be cultivated on land unsuitable for agriculture using saline or brackish waters. A limitation is that, differently from plants that obtain carbon from air, algae cultures must be supplied with CO_2 to be productive. The need to dissolve large amounts of CO_2 in the growth medium, wrongly perceived as an advantage, is an energy-intensive and expensive requirement of algae mass cultures, worsened by the fact that very few large-CO_2 emitters are located in the regions more suitable for year-round, large-scale algae production (e.g., dry tropical coastal regions) (Darzins et al. 2010).

In spite of the inherent potential of microalgae as a renewable fuel source and the many promises of recent years, there is no current industrial production of algae biofuel in the world. The higher capital and operating costs of microalgae farming compared to conventional agriculture, the non-sufficiently positive energy balance (after accounting for energy requirements for water pumping, mixing, CO_2 and nutrient supply, biomass harvesting and processing), and the not yet established sustainability (Lardon et al. 2009; Clarens et al. 2010; Borowitzka and Moheimani 2010) still prevent the development of this technology to commercial scale.

Today, microalgae (including cyanobacteria) biomass for commercial exploitation is either harvested from natural habitats or obtained through more or less controlled cultivation processes (Tredici 2004; Tredici et al. 2010). Commercial production of algae amounts to about 20,000 t annually, mainly marketed as high-value human nutritional supplements, specialty animal feeds and pharmaceutical products

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(Spolaore et al. 2006; Tredici et al. 2009). Commercial plants use one of the following four technologies:

1. extensive ponds (lagoons);
2. raceway and circular ponds;
3. tubular photobioreactors;
4. fermenters (where algae are grown on organic substrates in the dark).

The shallow raceway pond, in which the suspension is mixed with a paddle wheel, is the most common commercial system in use. All these systems have been considered for algae biofuels. Which technology will dominate the field in the future is not yet clear.

Most of the start-ups in the algae biofuel sector focus on photobioreactors (PBR). The reasons of the preference are:

1. PBR are closed to the atmosphere and protect the cultivated alga to some extent (note that by being closed, PBR are less prone, but not immune, to contamination);
2. growth parameters (e.g., temperature) can be better controlled;
3. due to a higher surface-to-volume (S/V) ratio, PBR allow to reach higher volumetric productivities and cell concentrations;
4. closed systems eliminate or strongly reduce evaporation;
5. since PBR have not been engineered to the extent of other bioreactors in commercial use (fermenters) there is room for improvement (Darzins et al. 2010).

Many different PBR designs have been proposed for biofuel production, few of them have been tested at pilot-scale, none developed at the (large) scale necessary for a complete and correct evaluation. Thus the main issues that impact on the reactor's performance (i.e., suitable construction materials, efficient mixing, heating/cooling, CO_2 supply and oxygen removal), although explored at pilot level, still await evaluation at real scale (Darzins et al. 2010).

Although the main limitations of PBR are the high cost and the reduced scalability (Lehr and Posten 2009; Tredici et al. 2010), with few exceptions, R&D on photobioreactor design is aimed at achieving high photosynthetic efficiencies and at pushing productivity beyond that currently attainable. The main strategies explored to this end are intensive mixing (Richmond 2004), light dilution via large external surfaces or internal light conducting structures (Zijffers et al. 2008a, b), and cultivation of improved or genetically modified strains (Radakovits et al. 2010). Most of this development is still in a very early stage and productivity projections are largely based on data from small-scale experiments. In reality, no company in the algae biofuel field seems to possess yet a mature technology able to compete with fossil fuels and be on the market in the near future.

Open ponds are much cheaper to build and operate than PBR, but they are strongly limited by contamination (by other algae, grazers, bacteria), the degree of which depends on climatic conditions (for example it is very difficult to maintain an open algal culture in the tropics during the rainy season), and the specific strain which is cultivated. Growing algae that require extreme conditions (e.g., high salinity or high pH) alleviates the problem. In fact, current commercial production is mainly based on algae such as *Dunaliella* and *Arthrospira* (*Spirulina*) that require extreme media for growth. Selection of a suitable strain and a favorable location for building the plant is fundamental. For example, some areas of the world (e.g., deserts) provide a more uniform environment that reduces the risk of contamination and the necessity of frequent intervention (for draining, cleaning, re-inoculation) (Darzins et al. 2010). Many believe that the solution is in combined systems (Huntley and Redalje 2007; Rodolfi et al. 2009): photobioreactors for inocula production followed by open ponds for bulk cultivation. Thus, even if the final choice for industrial production of algae biofuel will be open ponds, still reactors will be necessary for the first crucial step of producing strong and viable inocula. The main PBR used in commercial plants and tested at pilot level have been described elsewhere (Carvalho et al. 2006; Tredici 2004; Tredici et al. 2010). This chapter focuses on new designs mainly developed with the scope of biofuel production and/or CO_2 biofixation.

2 Recent Advances in Photobioreactor Design for Biofuel Production

In the last years PBR have much evolved and new designs have been proposed, most of them for research or small scale applications (Carvalho et al. 2006; Lehr and Posten 2009; Tredici et al. 2010). The high capital and operating costs of PBR have limited, and still do limit, their commercial application to the production of high-value products (biomass for aquaculture, food supplements, nutraceuticals, pharmaceuticals). Today, even if significant improvements are expected in large-scale PBR design thanks to new materials and automated process control systems, and by integrating skills in PBR engineering and solar technology (Lehr and Posten 2009; Tredici 2010), it is much debated if PBR will ever be used to produce "low-value" products such as biofuels and feed (Tredici et al. 2009; Tredici 2010; Darzins et al. 2010). For example, intensive research has been recently devoted to vertical systems that dilute light minimizing photosaturation and photoinhibition and thus maximize photosynthetic efficiency (PE) and areal productivity (see below). However, the achievement of a significant light dilution effect through vertical reactors requires large illuminated surface areas per unit ground area and consequently impacts heavily on investment and operating costs.

The principles leading to maximum productivities of algae culture systems are well known (Posten 2009; Tredici et al. 2010):

1. adequate mixing to provide a suitable light-dark cycle to the cells and avoid biofouling;
2. high mass transfer capacity to efficiently supply CO_2 and prevent O_2 build-up;
3. high S/V ratio to increase cell concentration and volumetric productivity;
4. control of temperature at or near the optimum for the cultivated organism;
5. accurate control of pH and CO_2 and nutrient concentrations;
6. adequate harvesting regime to maintain the optimal population density.

Most of the new PBR designs efficiently deal with the above requirements, their main drawback remaining a limited possibility of being scaled-up at low cost.

In the last few years, numerous companies targeting the field of microalgae biofuels have been established, with interesting new ideas or innovative applications of old PBR designs. There is also quite a large number of cooperative projects involving large corporations, including ExxonMobil Corp., Chevron Corp., Royal Dutch Shell Plc, Boeing, Raytheon, Honeywell UOP and General Electric.

In the following paragraphs most of the PBR designs tested at pilot level are described and the main current developments in the algae biofuel field are discussed.

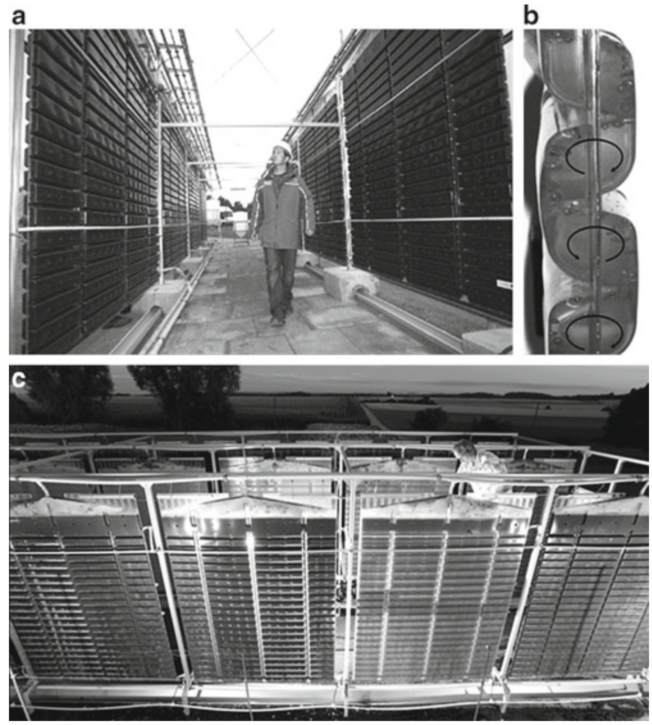

Fig. 7.1 Flat Panel Airlift reactor developed by Subitec GmbH. (**a**) Pilot plant in Hamburg-Reitbrook developed in cooperation with E.ON Hanse AG. (**b**) Side view of the panel with inbuilt baffles for induction of vortices (Courtesy of Subitec GmbH, ©Thomas Ernsting) (**c**) Plant in Eutingen-Weitingen (Stuttgart) developed in cooperation with EnBW AG

2.1 Flat Photobioreactors

Vertical or inclined flat reactors represent very promising culture devices. They can be oriented and tilted at different angles so as to modify the intensity of impinging light and use diffuse and reflected light, which plays an important role in productivity (Qiang et al. 1998; Tredici 2010; Tredici et al. 2010). Flat panels also offer the possibility to be closely packed together and thus attain, by a sort of "lamination" of the culture, high areal productivities (Carlozzi 2003; Wijffels and Barbosa 2010). In vertical or inclined plates, air-bubbling can be adopted for mixing ensuring at the same time adequate turbulence, a good mass transfer capacity, and scouring of the reactor walls. However, for air-bubbling to be efficient, relatively high bubbling rates must be adopted, and the cost of power supply may be high, especially when compared to the cost for mixing in raceway ponds (Bassi et al. 2010). Temperature control may be achieved both by water spraying (evaporative cooling) or by heat exchangers (Rodolfi et al. 2009). Several types of flat photobioreactors have been experimented with at pilot level outdoors (Tredici et al. 1991; Pulz and Scheibenbogen 1998; Degen et al. 2001; Zhang et al. 2001; Aflalo et al. 2007; Rodolfi et al. 2009). Some of the designs showing good scalability are described here.

A Flat Panel Airlift (FPA) photobioreactor, developed and patented in the early 2000s (Degen et al. 2001; Trösch 2002), has been recently implemented and scaled-up by **Subitec GmbH**, a spin-off company of the Fraunhofer-Institute for Interfacial Engineering and Biotechnology (Stuttgart, Germany) (http://en.subitec.com acessed 20 Jan 2011). The reactor is basically a plastic plate divided in large riser zones, in which compressed air is injected, and smaller down-comer zones (Fig. 7.1a, c). The riser zone is subdivided into interconnected horizontal chambers by means of baffles attached alternatively to the two wider sides of the reactor (Fig. 7.1b). The ascending air bubbles induce vortices that move the cells in and out the illuminated layers (Degen et al. 2001). FPA reactors from 3 to 33 L in volume have been successfully employed to grow several microalgae in the laboratory (Degen et al. 2001; Meiser et al. 2004) and outdoors (Schenk et al. 2008). At laboratory scale cell concentrations in the range of 10–16 g L^{-1} and volumetric productivities up to 1.5 g L^{-1} day^{-1} have been achieved with different microalgal species (Ripplinger 2009). Recent developments have been made into the direction of increasing reactor dimensions and reducing power supply from 500 to 200 W m^{-3} (Trösch

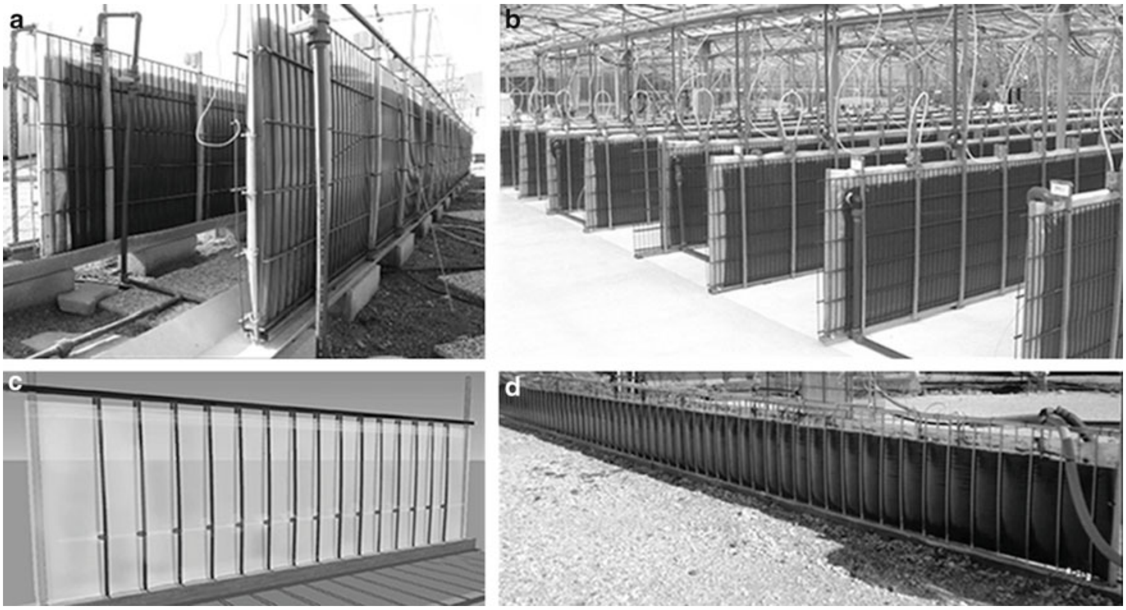

Fig. 7.2 Green Wall Panel (GWP) photobioreactors developed at the University of Florence (2004–2009) and commercialized by F&M S.r.l. (**a**) 20-m-long GWP prototype; (**b**) GWP pilot-scale plant (5,000 L) in operation at Microalghe Camporosso S.r.l. (Italy); (**c**) schematic drawing of a GWP-II; (**d**) 12-m-long GWP-II prototype (Photographs by the authors)

2009). The individual module of FPA reactors of the last generation consists of two deep-drawing polyvinyl chloride (PVC) or glycol-modified polyethylene terephthalate (PETG) shells welded together to form a 2.7-m-high, 5-cm-thick and 1.75-m-long reactor, containing 180 L of culture (Fig. 7.1a, c). The reactor cost is about €1 L^{-1}, equivalent to about €40 m^{-2} of reactor. In 2008 demonstration plants for CO_2 capture from waste gases were built in Hamburg (Germany) (two modules made of four reactors each for a total volume of 1.44 m^3), in cooperation with E.ON Hanse AG (Fig. 7.1a), and in Stuttgart (Germany) (three modules of eight reactors each for a total volume of 4.33 m^3) in cooperation with EnBW AG (Fig. 7.1c). Subitec GmbH is planning the construction of a plant of about 0.5 ha (180 m^3 total volume) in Spain (Ripplinger 2009; Trösch 2009). The main advantages of this system are industrial production of the plastic shells at relatively low-cost, good mixing and short light-path. At 1-ha scale, using 180-L FPA modules and assuming a productivity of 120 t ha^{-1} $year^{-1}$, capital costs of 1.5 M€ (of which 25% for the reactors) and operating costs of €2,200 t^{-1}, a biomass production cost of €4.2 kg^{-1} was calculated.

In 2006 a vertical panel reactor (named Vertigro*)* was developed and patented for production of oil-rich algae (Kertz 2007). The system consists of a series of closely-spaced, vertically-suspended panels made from thin plastic film. Each panel is divided into horizontal channels by welding the film, with the horizontal weldings shortened alternatively at one side or the other so as to allow communication between channels. The culture is pumped at the top of the reactor and circulates by gravity to the bottom in a meandering way. In 2007 a small scale plant was built in El Paso (Texas, USA) by Vertigro Algae Technologies, LLC, a joint venture between **Valcent Products, Inc**. and **Global Green Solutions, Inc**. (http://www.valcent.net/s/NewsReleases.asp?ReportID=344356, accessed 21 Jan 2011) using 3-m-high plastic panels, which were deployed under a greenhouse. The culture was held in an underground tank to maintain a constant temperature. To start the process, a pump pushed the culture up to a holding tank placed 3 m above the top of the plastic panels. Gravity then pulled the culture into the series of panels below. At the bottom, a collection chamber fed back the culture into the underground tank, where oxygen was removed and CO_2 added (Torrey 2008). During a 90-day test, an algal suspension at 1 g L^{-1} was continuously harvested. The company claimed to be able to achieve a productivity of more than 600 tonnes of dry biomass (and approximately 300,000 L of algae oil) per hectare and year (http://findarticles.com/p/articles/mi_pwwi/is_200712/ai_n21152992/?tag=content;col1, accessed 21 Jan 2011) which, if attained solely on solar energy input, is thermodynamically impossible (Tredici et al. 2010). The Vertigro system is interesting for its simplicity, high S/V ratio and verticality. Data on panel durability, oxygen accumulation and energy consumption are not available. Problems in such a high S/V ratio, low-turbulence system may arise at high cell densities that favour biofouling and because of oxygen build-up (Tredici et al. 2010). In 2009 the activity in the algae field of Valcent Products Inc. was closed and Vertigro Algae Technologies LLC dissolved (C. Harding, personal communication).

In the early 2000s the concept of the "disposable panel" was developed by two groups working independently in Italy (Tredici and Rodolfi 2004) and Israel (Boussiba and Zarka

2005). The group in Florence designed and patented the Green Wall Panel (GWP), a flat reactor comprising a culture chamber made of a 0.3-mm-thick flexible low-density polyethylene (LDPE) film enclosed in a rectangular frame of steel grids and vertical uprights. The typical GWP is 1-m-high, 4-cm-thick and 20-m-long and contains about 800 L of culture. Generally, the modules are placed vertically and facing south in parallel rows at a distance of about 1 m that, in Tuscany, prevents shading for most of the year (Fig. 7.2a). For mixing, compressed air is bubbled at the bottom of the reactor through a perforated plastic tube. CO_2 is injected into the culture through gas diffusers placed in unaerated zones. A control unit provides temperature regulation by automatically activating heat exchangers or water spraying on the reactor surface.

The GWP has been used to grow several marine microalgal species outdoors (Rodolfi et al. 2006). With *Tetraselmis suecica* grown in September in panels placed in parallel rows at a distance of 0.8 m wall to wall, it was shown that North-South oriented panels intercepted 22% more solar radiation and achieved a 35% higher areal productivity compared to East-West oriented panels (Rodolfi et al. 2008; Bassi et al. 2010). However, considering that the average annual solar radiation intercepted by vertical full-scale panels at a latitude of 43°N is similar for both orientations (about 7 MJ m^{-2} day^{-1}), annual productivities should not differ significantly between the two arrangements. Sierra et al. (2008) evaluated the fluid-dynamics and mass transfer characteristics of a 1.5-m-high, 2.5-m-long and 0.07-m-thick disposable panel. The study concluded that the low power supply (53 W m^{-3}) and the high mass transfer capacity make bubbled plates preferable to pump mixed tubular PBR. A complete energy analysis for the GWP is reported later in this chapter.

Using GWP reactors, the potential of the marine eustigmatophyte *Nannochloropsis* sp. as a source of renewable oil was thoroughly investigated by Rodolfi et al. (2009). In a two-phase cultivation process (a nutrient sufficient phase to produce the inoculum followed by a nitrogen deprived phase to boost lipid synthesis) the lipid content of the biomass was increased up to 60% and lipid productivity was doubled in comparison with a nutrient sufficient single-phase process (100 and 204 mg lipid L^{-1} day^{-1}, respectively). Experiments carried out in a "full scale" simulation showed that *Nannochloropsis* sp. has the potential for an annual lipid production of 20 t ha^{-1} in the Mediterranean climate (Rodolfi et al. 2009). Nutrient deprivation has been shown to increase neutral lipids up to 48% of dry biomass, with the triacylglycerols (TAGs) representing the most abundant component (Bondioli et al. 2010). Pilot scale GWP reactors for CO_2 bio-sequestration are currently in operation at ENI S.p.A. (Gela, Italy), ENEL Ingegneria e Innovazione S.p.A. (Brindisi, Italy) and Bioscan S.A. (Antofagasta, Chile). The GWP is used for commercial production of algae biomass by Necton S.A. (Olhão, Portugal) and Microalghe Camporosso S.r.l. (Imperia, Italy) (Fig. 7.2b).

The GWP design has been recently modified in order to reduce its cost (Tredici et al. 2011). In the new design (GWP-II) the grids have been removed and the culture chamber is contained within a simple structure made by a base and a number of vertical uprights driven directly into the base or into the ground (Fig. 7.2c, d). A 0.7-m-high, 4-cm-thick and 12-m-long prototype has been tested with *T. suecica*, *Cylindrotheca* sp. and *Scenedesmus* sp. The removal of the grids and the reduction of the culture chamber height from 1 to 0.7 m have allowed the use of a much lighter metal frame and decreased the reactor's cost from €50 to about €25 m^{-2}. A further improvement, that envisages dividing the unique culture chamber into two or more horizontal sections (Tredici et al. 2011) is expected to bring the cost of the reactor to about €5 m^{-2} (Tredici 2010).

The main advantages of the GWP designs are the low construction cost and the capacity to be scaled-up. The main limitation are the high energy expenditure for mixing and cooling (Tredici 2009; Bassi et al. 2010). GWP reactors are commercialized by **Fotosintetica & Microbiologica S.r.l.** (Florence, Italy), a spin-off of the University of Florence (http://www.femonline.it, accessed 23 Jan 2011).

Solix Biofuels® (http://www.solixbiofuels.com, accessed 21 Jan 2011) a spin-off of the Colorado State University (Fort Collins, Colorado, USA), has developed a low-cost reactor, the Algae Growth System (AGS), for biofuel production (Willson et al. 2008, 2009). The G3 design, the last of three generations of AGS (Fig. 7.3), comprises a series of vertical panels made of welded flexible plastic film, which are submerged in a shallow water basin to provide mechanical support and temperature control. Carbon dioxide enriched air is bubbled through sparging tubes to regulate pH, remove dissolved oxygen and provide adequate mixing of the algal suspension (Buehner et al. 2009; Willson 2009a). The system combines large reactor surface areas per land area to reduce light intensity (light lamination) with an external water basin for structural support and thermal regulation (Willson 2009a). In the G4 design under development gas exchange will be achieved by permeable membranes placed inside the culture (Willson 2009b; Willson et al. 2009).

A model-based control system has been developed to estimate microalgae growth, O_2 production and CO_2 consumption as a function of incident light. The model has been validated with *Nannochloropsis oculata* in a 644 L PBR made of four panels, 17-m-long, 0.33-m-high, and 0.03-m-thick (Buehner et al. 2009). Experimental results correlated well with the model and showed that automation is necessary to maximize growth and achieve cost targets (Buehner et al. 2009; Willson et al. 2010). The cost of large-scale oil production with the current AGS technology was estimated to be US$1 L^{-1} (Willson 2009a).

Fig. 7.3 Solix Biofuels® photobioreactor at the Coyote Gulch demonstration facility in Southern Colorado (USA) (Courtesy of Solix Biofuels®)

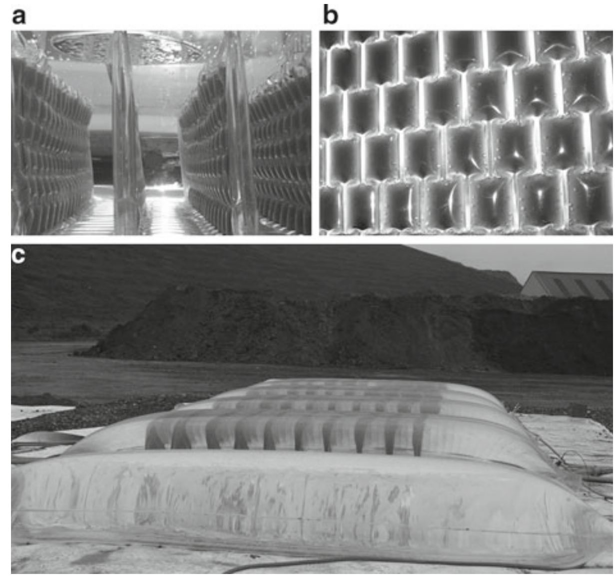

Fig. 7.4 ProviAPT photobioreactor developed by Proviron Holding NV (Belgium). (**a**) submerged panels; (**b**) detail of interconnecting compartments; (**c**) pilot plant in operation at an ex-municipal waste site (Courtesy of Proviron Holding NV)

The practical maximum annual oil production at the latitude of Denver (Colorado, USA) (40°N) and with 50% cell oil content, was calculated to be 44,000 L ha^{-1} (Weyer et al. 2010), a value that exceeds by more than 100% the potential annual lipid production estimated by Rodolfi et al. (2009) for Mediterranean regions. According to company information, microalgae (no details about the species are provided) grown at Solix site in Colorado have yielded 16,800 L of oil ha^{-1} year^{-1} (i.e. 38% of the maximum expected). Currently, a demo plant made of three basins covering a surface area of 0.1 ha each (Fig. 7.3) is in operation at Coyote Gulch in Southern Colorado (USA) (www.solixbiofuels.com; Willson 2009b). The Coyote Gulch demonstration facility is co-located with a coal-bed methane production plant and uses the wastewater generated during coal-bed methane production and the CO_2 produced by the amine plant to feed the microalgae culture.

A water-filled plastic bag PBR that incorporates a series of thin panels (less than 1 cm thick) of low height (about 0.5 m), has been recently developed by **Proviron Holding NV** (Hemiksem, Belgium) (www.proviron.com, accessed 22 Jan 2011). The innovative concept of this design (named ProviAPT) is that the plastic bag, including all the panels and connections, is automatically produced and the setup is limited to rolling out the bag and filling it with water (Michiels 2009). Due to water pressure from outside that balances the interior pressure of the culture suspension, the panels are self-supporting and take on a vertical position without any need of a supporting structure (Fig. 7.4a). Mixing of the culture suspension and pH control are obtained by bubbling CO_2 enriched air. Each panel is internally partitioned to form small interconnecting compartments (Fig. 7.4b). This special pattern reduces the rise velocity of the bubbles ensuring a more efficient utilization of the air stream. Among the advantages of this system there are the short optical path and the large volume (500 L m^{-2}) of water surrounding the panels, which provides temperature buffer without the need of additional thermoregulatory systems. According to company information about 2.5 kg of plastic foil are used per square meter of reactor with an investment cost of less than €10 m^{-2}. The energy input is about 2 W m^{-2}, mainly due to air-bubbling (http://www.proviron.com/algae/pdf/GB/ProviAPT_01.pdf, accessed 22 Jan 2011). A pilot plant that comprises four bags (each bag is 4-m-long and 1.5-m-wide and contains ten panels) and covers about 24 m^2 land area is in operation in an ex-municipal waste site where biogas is produced (Fig. 7.4c) (M. Michiels, personal communication, 2010). A 270-L ProviAPT unit has been installed at AlgaePARC (Bennekom, The Netherlands) (M. Barbosa, personal communication, 2011). The main drawbacks of this design are difficult accessibility to the culture and risks with punctures of the bag that could cause the collapse of the panels. The performance of ProviAPT has been not yet fully tested, and its reliability and scalability remain to be demonstrated.

Fig. 7.5 Accordion photobioreactor developed at the University of Arizona (USA) (Courtesy of Prof. JL Cuello)

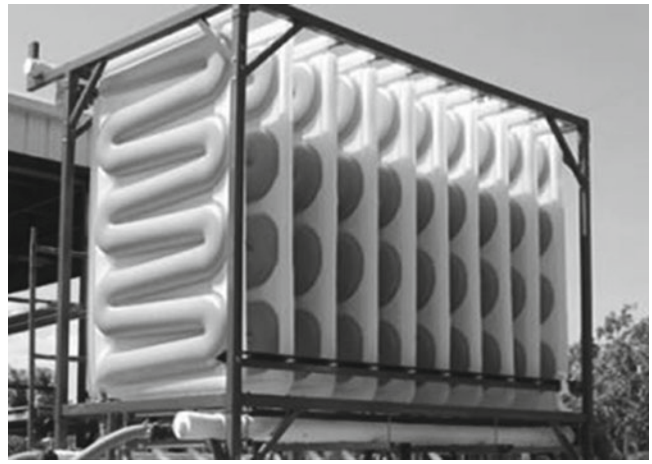

Fig. 7.6 Vertical plates developed by Renewed World Energies Corp. (USA) (Reproduced with permission from the company's web site)

At the University of Arizona (USA) the research team of Prof J. Cuello is developing a new design called "Accordion". The system, made of thin polyethylene film, consists of a series of vertical sinuously bent sleeves mounted on a metal framework (Fig. 7.5). The algal suspension is pumped to the top of the system and flows down from section to section (Cuello and Ley 2010). The Accordion has been used to grow *Botryococcus braunii*. The University is negotiating with the Norwegian company Biopharmia AS a licensing option. Among the advantages of the system there are the large illuminated surface area that maximizes the light dilution effect, the high S/V ratio and the possibility to vary the bending angle of the sleeves to modify the velocity of the descending flow and the incidence angle of light and thus irradiance on the reactor surface. Data of productivity, energy consumption, and costs are not available.

A vertical PBR called "Hanging Gardens" has been recently developed and patented by **Ecoduna OG** (Hainburg, Austria) (Mohr and Emminger 2009; http://www.ecoduna.com, accessed 21 Jan 2011). The system consists of a series of closely spaced, 6-m-high rigid vertical plates hung within a movable structure which allows the plate arrays to track the sun movement. The plates are internally partitioned into interconnected channels by means of inner vertical walls shortened alternatively at the bottom and at the top so as to allow circulation of the culture suspension. CO_2 injected at the bottom of the reactor is used to generate a gas-lift effect, to remove the O_2 produced by photosynthesis and as carbon source. The use of pumps for mixing is minimal. The PBR provides an illuminated surface area of 32 m^2 and a culture volume of about 440 L on each square meter footprint. Among the advantages of the system, the reduction of energy for mixing, the large illuminated surface area and the efficient utilization of land are claimed to be the most important. Besides, it is reported that, since the reactor acts as a solar tracker, mutual shading between the units is avoided. It remains to be proved that CO_2 injection in response to pH increase might be adequate to provide mixing and oxygen removal. Another limitation of this concept is the greatly increased amount of reactor material and supporting structures, which enhances capital costs significantly.

Renewed World Energies (RWE) **Corp.** (Georgetown, South Carolina, USA) developed and patented a photobioreactor, which consists of a series of closely spaced vertical plates held in a rack. Each plate (approximately 1.2-m-wide, 1.8-m-high, and 0.08-m-thick) is made from high-density polyethylene (HDPE) sheets thermoformed to create a flattened tubular serpentine culture chamber (Fig. 7.6). Water, nutrients and gases are circulated through the panels by means of piping header connections (www.rwenergies.com, accessed 22 Jan 2011). An automated process control system regulates algae growth and harvesting with minimal operator inputs. The company presented a prototype of the PBR at the Algae Biomass Summit Conference in San Diego in October 2009 (http://www.youtube.com/watch?v=J2cc2bGBuvo, accessed 21

Fig. 7.7 Vertical tubular serpentine PBR developed by the Department of Chemical Engineering of the University of Almeria (Spain) (Courtesy of Prof. E Molina Grima)

Jan 2011). Among the limitations of the system are the heavy structure and the low transparency of the HDPE sheets that form the culture chamber.

2.2 Tubular Photobioreactors

Tubular photobioreactors are the most common design available and the preferred one in commercial algae production (Tredici et al. 2010). These reactors are usually constructed with either glass or plastic tubes in which the culture is circulated with pumps or preferably by means of airlift systems. They can be either serpentines or manifolds and have a horizontal (Chaumont et al. 1988; Molina Grima et al. 2001), vertical (Pirt et al. 1983), inclined (Lee and Low 1991; Torzillo et al. 1993; Tredici and Chini Zittelli 1998; Ugwu et al. 2002) or conical (Watanabe and Saiki 1997) arrangement. Advantages and limitations of tubular photobioreactors have been discussed in numerous reviews (Sánchez Mirón et al. 1999; Janssen et al. 2003; Tredici 2004; Tredici et al. 2010).

Among the pilot-scale plants devised for algae biofuel production, special mention deserves the serpentine reactors developed at the Department of Chemical Engineering of the University of Almeria (Spain) by the research group of Prof Molina Grima and in operation under a greenhouse at the Estación Experimental de Cajamar "Las Palmerillas" (Almeria) (Fernández-Sevilla et al. 2010). A two-layer, 4,000-L horizontal tubular PBR, made of 10-cm diameter Plexiglas® tubes connected by U-joints to form a single 400-m long loop, has been used for production of lutein-rich biomass of *Scenedesmus almeriensis* (Fernández-Sevilla et al. 2008, 2010). With this freshwater microalga an oil production potential of about 16 t ha^{-1} year^{-1} has been estimated (Molina Grima 2009). The system has been redesigned and is now composed of ten 2.8 m^3 vertical serpentine units. Each unit occupies a surface area of about 50 m^2 and consists of 20-m-long, 9-cm-diameter Plexiglas® tubes running in a fence-like structure (Fig. 7.7). The loop outlet is connected to a 3.2-m-high downcomer connected to the inlet of the loop. The culture suspension is circulated by a centrifugal pump (Molina Grima 2006). The plant is fully automated and the process is controlled by specially-designed software (Molina Grima 2009; Fernández-Sevilla et al. 2010). Adopting a dilution rate of about 35% a mean volumetric productivity of 0.4 g L^{-1} day^{-1} (corresponding to an areal productivity of about 20 g m^{-2} day^{-1}) was attained in winter with *Nannochloropsi*s (F.G. Acién Fernández, personal communication, 2010). The biomass production cost in this plant was estimated to be around €25 kg^{-1} (Molina Grima 2009). According to the authors, to reduce the cost of biomass to less than €0.5 kg^{-1} (necessary for energy applications), PBR cost should be less than €1 L^{-1} and personnel should be reduced to less than 0.5 persons per hectare (Acién Fernández 2008).

In Spain, one of the most active companies in the algae biofuel field is **Algaenergy SA** (Madrid) (http://www.algaenergy.es, accessed 22 Jan 2011). Starting from technology acquired from universities (University of Seville, University of Almeria, University of Santiago de Compostela) and research centres (Consejo Superior de Investigaciones Científicas), the company aims at industrial scale microalgae cultivation using different PBR designs and ponds. Algaenergy SA has invested in the construction of the tubular pilot plant in operation at "Las Palmerillas" and is building a 10,000 m^2 pilot plant based on flat panel PBR. (http://rp7.ffg.at/Kontext/WebService/SecureFileAccess.aspx?fileguid=%7B3aa74614-4d8e-4328-883e-6e4c64bd071c%7D, accessed 18 Jan 2011). Two Spanish leaders in renewable energy and biofuels, Iberdrola SA and Repsol S.p.A., are shareholders and technology partners in Algaenergy SA.

Since 2007 **AlgaeLink NV** (Yerseke, The Netherlands) commercializes a horizontal serpentine PBR made of large-diameter transparent plastic tubes (Van de Ven and Van de Ven 2009). The company offers systems from demo (3.8 m^3) to large-scale (140 m^3) size, equipped with feeding and control units, an automatic cleaning device, filters for harvesting and equipment for solar drying (www.algaelink.com, accessed 23 Jan 2011). A 97 m^3 system (1,200 m^2 occupied area) made of 2,000-m-long, 25-cm diameter poly(methyl methacrylate) (PMMA) tubes is sold for €194,000 (http://www.algaeglobal.com/algaelink%20com%20cult.htm, accessed 23 Jan 2011). This is an interesting price (about €160 m^{-2}) for a completely-controlled, self-cleaning, pump-mixed closed PBR, which includes harvesting and solar drying equipment. The company expects to reach, with algae of the genus *Tetraselmis,* productivities of 160 t ha^{-1} year^{-1} in The Netherlands and 300 t^{-1} ha^{-1} year^{-1} in Australia, (Van den Dorpel 2010), which correspond to photosynthetic efficiencies of about 8% on total solar energy, never obtained outdoors at large scale.

GreenFuel Technologies Corp. (GFT) (Cambridge, Massachusetts, USA), founded in 2001 by Massachusetts Institute of Technology (MIT) and Harvard scientists, used a tubular airlift PBR to cultivate microalgae on gas emissions from a power plant, aiming at simultaneously scrubbing the flue gases and producing biofuels (Tredici et al. 2010). In 2004 the reactor was tested at the MIT cogeneration power plant (Massachusetts, USA). The reactor consisted of a set of riser tubes, gas separators and downcomer tubes arranged in a triangular configuration. The gas was injected at the bottom, and the difference in fluid density between the riser and the downcomer provided the driving force for liquid circulation (Berzin 2005; Vunjak-Novakovic et al. 2005). It was claimed that more than 80% of CO_2 and NOx could be removed from the flue gas and biodiesel productivities of 80 t ha^{-1} $year^{-1}$ were attainable (Vunjak-Novakovic et al. 2005; Tredici et al. 2010). The triangular photobioreactor geometry was later changed to simple inclined tubes and a pilot unit was tested using algae selected for their high oil and starch production potential at the Arizona Public Service Redhawk power plant in 2006. In 2007 a final design, called the 3D Matrix System (3DMS), was tested at the GFT facilities in the Arizona desert (Pulz 2007). According to company press releases, with this technology an average biomass areal productivity of 98 g m^{-2} day^{-1} was achieved, with peak values of over 170 g m^{-2} day^{-1} on good sunny days (Pulz 2007). Even if the 3DMS was reported to have a S/V ratio of 1,500–2,000 m^{-1} and a very high illuminated surface area per areal footprint (that maximized the "light dilution effect"), these productivity values are unrealistic. The peak productivity value would correspond to a photosynthetic efficiency on total solar radiation of about 18%, i.e., 1.5 times the theoretical maximum for algal biomass production (Tredici 2010).

GFT, with its significant efforts to integrate their technology into power plants, in the USA, South Africa and Europe, renewed the interest in algae biofuels, after many years of dormancy probably due to the negative conclusions of the DOE project ended in the 1990s. Cost concerns and the difficulty to fully control algae growth seemingly have hampered the company to continue. GFT officially announced closing down operations in May 2009 (Kanellos 2009). All the details here provided are based on data gathered prior to company's closure.

Recently **Sogepi S.r.l.** (Milan, Italy) and **F&M S.r.l.** (Florence, Italy) have jointly developed a 5 m^3 manifold tubular reactor for CO_2 biofixation and production of algae biomass as feedstock for feed and biofuel (Giudici and Tredici 2010). The tubular section of a module, made of 10 m-long, 9-cm-diameter, PMMA tubes joined by PVC flanges and connected at the end to steel manifolds, occupies about 100 m^2. Circulation and mixing are achieved by means of a rotary lobe pump. Cooling and oxygen removal are obtained by circulating the culture through a cooling tower (Fig. 7.8). In the summer 2010, a 5,000-L prototype was built and tested at F&M S.r.l. experimental field (Florence).

Fig. 7.8 Manifold tubular reactor developed by Sogepi S.r.l. (Milan, Italy) and F&M S.r.l. (Florence, Italy) (Photographs by the authors)

Diversified Energy Corp. (Phoenix, Arizona, USA) is commercializing a closed system called Simgae™ (for simple algae) invented and patented by **XL Renewables Inc**. Aiming at agricultural levels of simplicity, the Simgae™ culture system utilizes a series of transparent, thin-walled polyethylene tubes (named Algae Biotape™) similar to conventional drip irrigation tubes, that are laid across the field in troughs created by means of traditional farming equipment. The tubes are V-shaped at the bottom. CO_2 –enriched air injection, nutrient addition and water circulation is achieved by pumps and piping available in the agriculture industry. Oxygen is removed through vents placed on the top of the tubes. By avoiding complex systems, Diversified Energy Corp. aims to lower capital costs of the technology below US$50,000 ha^{-1}. Simgae™ annual yield is estimated to be about 50 t dry algal biomass per hectare, with an oil content ranging from 20 to 30% (http://www.diversified-energy.com, accessed 23 Jan 2011). The advantages of the system include: (1) a simple design based on common agriculture components and processes; (2) easy installation, operations and maintenance; (3) low capital cost (even below that of raceway ponds). However, the commercial exploitation of the Simgae™ technology for production of biofuel still requires development and optimization of the process (above all improvement in oxygen removal, thermoregulation, biofouling control).

A2BE Carbon Capture, LLC (http://www.algaeatwork.com, accessed 23 Jan 2011) (Boulder, Colorado, USA) is developing a technology that combines algae farming-based CO_2 capture with production of biofuels, animal feed, protein and fertilizer. The core of the technology is the Carbon

Fig. 7.9 Biological Algae Growth Systems (BAGS) developed by MBD Energy Ltd (Australia) (Courtesy of MBD Energy Ltd)

Capture & Recycle Roller-Film photobioreactor (CC&R PBR) for growing and harvesting algae (Sears 2007). Each module is approximately 137 m long and 15 m wide and consists of twin 6-m-wide, 0.25-m-deep, 122-m-long, transparent plastic reactor tubes connected to end gas exchangers. One module covers about 0.2 ha (Sears 2009). Two rollers (0.6 m in diameter, 6-m long each) push and re-suspend the microalgae through the tubes also cleaning the inner tube walls. In addition to moving the culture suspension, the rollers favour degassing by pushing the oxygen bubbles towards the end of the tubes where they are collected and released through vents. Flue gas emissions rich in CO_2 and NOx or pure CO_2 are introduced through perforated membranes placed at the bottom of the water column in which the water flows in opposite direction to bubble movement (Sears 2007). According to company information the annual CO_2 consumption of the CC&R PBR was estimated to be about 250 t ha^{-1} and biomass productivity 140 t ha^{-1} year^{-1}, values which appear too optimistic.

The "Biological Algae Growth System" (BAGS), recently developed by **MBD Energy Ltd** (Melbourne, Australia) can be considered a hybrid system, i.e., it combines the characteristics of open ponds and photobioreactors. The BAGS consists of a series of large horizontal bags made of flexible plastic film, partially filled with the culture suspension and including a large gas space above the culture (Fig. 7.9). Injection of flue-gas at the bottom of the culture allows mixing and deoxygenation of the culture suspension, favours distribution of nutrients and maintains the cultivation chamber inflated (www.mbdenergy.com, accessed 24 Jan 2011; Stammbach et al. 2010). The growth of *Nannochloropsis oculata* was tested in a 10-m-long, 3-m-wide bag, filled up to 30 cm so as to have a final culture volume of about 9 m^3. In a 20-day trial the mean productivity obtained was about 1×10^6 cells mL^{-1} day^{-1} (i.e., about 2 g m^{-2} day^{-1}) (Stammbach et al. 2010). In collaboration with the James Cook University (Townsville, Australia), MBD has developed a 5,000-m^2 facility potentially capable of producing 14,000 L of oil and 25,000 kg of algal meal from every 100 t of CO_2 consumed. The company is currently moving from test facility to full scale plants (1 ha) to be built at a number of Australia coal-burning power stations. This reactor couples the advantages of open systems (e.g., inexpensive construction) and closed PBR (e.g., a closed and controlled environment). The inside positive pressure in the bags also helps in limiting contamination. However, further testing on the field scale is necessary for a complete evaluation of the potential of the system at large scale.

2.3 Innovative Concepts

To achieve high biomass areal yields, a PBR should capture as much sunlight as possible and distribute it to the cells in such a way (uniformly and at low irradiances) so as to allow high efficiencies of conversion into biomass. High diurnal irradiances, necessary on the other hand for high areal productivity, make this goal difficult to achieve. A solution seems, at least from the theoretical point of view, to develop systems in which photon capture is physically separated from the cultivation phase and light is then distributed, at adequate intensity, via conducting structures within the culture.

Fibre-optic-based systems in which visible solar light is collected by mirrors, concentrated through lenses and delivered into the bioreactor via an array of flexible, optical fibres or transparent bars or plates, have been developed and tested at laboratory scale (Mori 1985; Ogbonna et al. 1999; Feuermann et al. 2002; Gordon 2002). Wijffels and his team at the Bioprocess Engineering Group of the Wageningen University (The Netherlands) envisaged a rectangular airlift photobioreactor 10-m-high, 250 m^3 in volume, containing 83-cm-thick light-re-distributing plates placed 3 cm apart. Solar light would be collected by parabolic dishes from a field of about two hectares and conveyed through optical fibres to the plates that redistribute visible photons inside the culture at an average irradiance of 1,200 µmol photons m^{-2} s^{-1}. Assuming a 15% photosynthetic efficiency (too high for that irradiance), the authors estimated that the annual productivity of such a system would reach 200 tonnes of dry algal biomass (Janssen et al. 2003), i.e. 100 t ha^{-1} of collecting surface.

More recently, the same group has developed the Green Solar Collector (GSC), a reactor in which sunlight is captured through PMMA Fresnel lenses that are able to rotate over two axes to follow the sun. Light focused on top of PMMA distributing elements (light-guides), refracts into the light-guides and propagates downwards by total internal reflection. Refraction out of the triangular shaped bottom part of the guides distributes light into the culture compartments (Zijffers et al. 2008a, b; Zijffers 2009). Efficient capturing of sunlight and redistribution inside the algal culture can be achieved in the GSC at high elevation angles of the sun, making the GSC suitable for operation at low latitudes with high level of direct irradiance (Zijffers et al. 2008b). Compared to optical fibre systems, the GSC technology appears more efficient because focusing sunlight directly on the light guides reduces losses caused by attenuation in the fibres. Moreover, light reflects internally without loss in intensity over the small distance where it needs to be transported (Zijffers 2009). Due to the very high cost of solar tracking devices and distribution systems, these technologies are prohibitive for low cost algae feedstock production, but expected progress in materials for photon capture and transport makes this approach promising in the long run.

A limiting factor in any system for algae cultivation, whether an open pond or a PBR, is the short penetration of light into the culture. Based on the work of Prof Amos Richmond (Ben-Gurion University of the Negev, Israel) and using the patented "light distribution" technology devised by Zweig in 2010, **Algaenesis Ltd** (Jerusalem, Israel) has developed an innovative system that can be integrated into an open pond and is capable of capturing, without tracking, all incident sunlight and distribute it evenly throughout the culture volume. It consists of an optically transparent light concentrator/redirector device made of a series of rectangular prisms. After refraction on the curved upper surface of each prism, light is propagated into conducting channels and transferred deeply and evenly within the culture (Zweig 2010). According to company information, since impinging light is diluted ten times before being delivered to the culture, the technology would allow to attain efficiencies and productivities five times greater than those attainable with conventional systems (http://www.algaenesis.com, accessed 4 Feb 2011).

Several companies in Europe and USA have developed technologies that exploit the tendency of microalgae to grow attached on solid substrates and form biofilms. A pilot-scale photobioreactor that uses fixed-film membranes has been built at the Ohio University's Coal Research Center (Athens, Ohio, USA) for photosynthetic CO_2 fixation. In this membrane-based photobioreactor, known as Carbon Recycling Facility (CRF), the algae grow on woven-fibre membranes suspended vertically in a reaction chamber where both flue gases and the growth medium are continuously circulated. Parabolic mirrors mounted on the top of the reactor collect sunlight and channel it along fibre-optic cables which in turn deliver light to illuminating panels interspersed between the membranes. By increasing the medium flow a high shearing force is obtained that forces the algae off the membranes (Bayless et al. 2002, 2006; Mears 2008) for harvesting. The bioreactor has been tested with the thermophilic cyanobacterium *Chlorogleopsis* sp. It was reported that the cyanobacterium can be grown on saturated hot flue gas with productivities ranging from 10 to 50 g m^{-2} day^{-1} as a function of irradiance (Bayless et al. 2006). Growing microalgae on membranes minimizes water use and reduces harvesting cost. However, the technology is restricted to microalgae able to grow in attached state. **GreenShift Corp.** (Alpharetta, Georgia, USA) (http://www.greenshift.com, accessed 4 Feb 2011), under a license agreement with the Ohio University, is conducting experiments with the CRF for reducing greenhouse gases emissions from fossil-fuel combustion processes.

On an industrial scale **SBAE Industries NV** (Sleidinge, Belgium) has developed and patented a technology, called DIAFORCE™, for the outdoor production of diatom polycultures (www.sbae-industries.com, accessed 4 Feb 2011). The DIAFORCE™, imitating nature, adopts specially designed triangle carriers, on which artificial substrata are mounted, that are placed in the water stream and upon which a community of diatoms can grow. Typically the water stream is wastewater and the flow is controlled (Vanhoutte and Vanhoutte 2009). Harvesting is achieved by an automatic device, which travels the length of the system, lifting the carriers covered with the diatoms out of the water stream, and blows or rinses the biofilm into a collector, then replacing the carriers back into the water channel (Vanhoutte and Vanhoutte 2010). Compared to conventional systems this method reduces the water to be processed by over 95%. According to tests carried out in 200 m^2 plants, a DIAFORCE™ reactor can produce 100 t ha^{-1} year^{-1} of biomass in temperate climates. SBAE has plans to realize facilities (from 5 to 50 ha) in the next 2 years to produce algae feedstock for feed and fuel (Van Aken 2009). Although it can be applied only to poly-cultures, the DIAFORCE seems suitable to grow algae in different environments, with the advantage of low water use and economical harvesting.

A biofilm based approach is also applied by **BioProcess Algae, LLC** (Portsmouth, Rhode Island, USA) for CO_2 capture. The company has developed and patented a system known as Grower Harvester™ bioreactor, for growing attached microalgae under autotrophic, heterotrophic or mixotrophic conditions and harvesting the algal biomass (www.bioprocessalgae.com, accessed 4 Feb 2011; Ahrens et al. 2009; Ahrens 2010). The system includes a plurality of cylindrical containers that can be arranged either vertically or horizontally. Each cylinder contains specially-designed substrata, at least partially submerged in the water, that serve for the attachment of microbial cells. The substrata are supported on a rotary frame to improve utilization of light. The system includes a flushing device that sprays the substrata and removes the attached microalgae (Haley 2010; Ahrens 2010). A demonstration unit installed at the ethanol plant of Green Plains Renewable Energy, Inc. in Shenandoah (Iowa, USA) has been operating continuously since October 2009 using the plant recycled heat, water and CO_2.

OriginOil, Inc. (Los Angeles, California, USA) has recently developed a new technology to produce oil from microalgae. The cultivation system, known as "Helix

BioReactor™" features a rotating vertical shaft with low-energy lights arranged in a helix or spiral pattern, which results in a theoretically unlimited number of growth layers. Each lighting element can produce specific light wavelengths for optimal algae growth (www.originoil.com, accessed 4 Feb 2011; Shigematsu and Eckelberry 2009). This design has been recently applied in pilot systems, which consist of a series of LED light sticks placed inside an 800-L algal culture tank (Sula 2010). The company has also developed a process for algae oil extraction where Quantum Fracturing™ is combined with electromagnetic pulses and pH modification to break the algae cells and release their oil content. The oil rises to the top and can be skimmed, while the remaining biomass settles to the bottom. Recently, the company announced that a process has been developed by which algae oil can be continuously extracted without cell damage in a sort of milking. OriginOil, Inc. has recently entered into a partnership agreement with MBD Energy Ltd, which is regarded as a pioneer in the use of exhaust (flue) gases as feedstock to produce algal biomass.

2.4 Combined Production Processes: Coupling Ponds and Photobioreactors

Raceway ponds are less expensive than PBR. However, being open to the atmosphere, algae cultures in open ponds easily become contaminated with unwanted algal species and grazers. PBR, being closed, minimize air-borne contamination, but have higher installation and operation costs. A combination of both systems seems a promising strategy for cost-effective cultivation of selected strains for biofuel production. Besides, it can be well adapted to two-stage cultivation processes (Rodolfi et al. 2009): the first stage, carried out in the PBR to produce the inocula; the second stage, carried out in the pond, to obtain the main product (e.g., biomass, oil). Since the cultivation in the pond lasts only few days, there will be not time for contaminants to develop and prevail.

Huntley and Redalje (2007) described a coupled process for the production of oil and astaxanthin from *Haematococcus pluvialis*. The plant was made of 25,000-L tubular photobioreactors and 50,000-L open ponds. The module consisted of a 200-m^2 horizontal serpentine reactor made of low-density polyethylene tubing (38 cm in diameter). Temperature was controlled by immersion of the reactor in a water pond. The culture grown in the PBR was used to inoculate the raceway ponds in which the cells, exposed to stresses (high irradiance, low nitrogen), accumulated both astaxanthin and oil. The coupled system achieved an average annual biomass productivity of 38 t ha^{-1} with an oil production rate of about 10 t ha^{-1}.

A dual cultivation process, called ALDUO™ technology, which uses PBR for continuous cultivation and open ponds for batch cultivation has been developed and patented by **HR BioPetroleum, Inc.** (Kailua-Kona, Hawaii, USA) (http://www.hrbp.com, accessed 18 Feb 2011). The technology aims to convert industrial CO_2 emissions into algae biomass to be further processed into biofuels and other useful products (Huntley and Redalje 2010). In 2007 HR BioPetroleum, Inc. and **Royal Dutch Shell Plc** established a joint-venture company, called **Cellana,** to build and operate a 2.5-ha demonstration facility in Hawaii for growing marine algae for biodiesel. In February 2011 Royal Dutch Shell Plc decided to relinquish its stake in Cellana and HR BioPetroleum, Inc. assumed full ownership (Sims 2011).

3 Energy Needs for Algae Biomass Production in a Disposable Panel Reactor

The many different reactor designs here described cannot be fully evaluated because of lack of long experiments able to provide reliable data on productivity, durability, sustainability at large scale. An issue of utmost importance, when biofuel production is the target, is a thorough analysis of the energy balance of the process. In this paragraph the energy balance of algae biomass production in a disposable panel reactor is illustrated.

Recently, based on the experimental data published by Rodolfi et al. (2009) a comparative analysis of the energy life-cycle for production of biomass and oil from *Nannochloropsis* has been published (Jorquera et al. 2010). The net energy ratio (NER), i.e., the ratio of the total energy content of the oil and the residual biomass over the energy content of the system construction plus energy required for all operations, of three different systems (GWP, tubular reactors and ponds) was calculated. The NER in the GWP was largely positive: 4.5 for whole biomass and 1.6 for oil. Harvesting and oil extraction energy costs were not considered. The results of this analysis appear too optimistic as shown by the calculations reported below.

Optimal bubbling rates for *Nannochloropsis* in the GWP vary between 0.15 and 0.45 L (of air) L^{-1} (of culture) min^{-1} (Bassi and Tredici, unpublished). The GWP typically contains about 40 L of culture per meter of panel (equivalent to 40 L of culture per square meter of occupied land area when the panels are deployed at 1 m distance) and has an average cross sectional area of 0.04 m^2. Considering an optimal bubbling rate of 0.3 L L^{-1} min^{-1}, corresponding to a superficial gas velocity of 0.3 m min^{-1}, a power of 1.96 W m^{-2}, equivalent to 85 kJ m^{-2} day^{-1} when the culture is mixed for 12 h a day, is required, according to the formula given by Chisti and Moo-Young (1989) (see footnote). Considering actual air-compression costs (Metcalf & Eddy, Inc, 2003), the cost for mixing rises to 142 kJ m^{-2} day^{-1}. The embodied energy and the energy cost for cooling in the GWP have been calculated to be about 300 and 35 kJ m^{-2} day^{-1}, respectively (Bassi and Tredici, unpublished). A typical productivity of 20 g m^{-2} day^{-1} and a biomass energy content of 20 kJ g^{-1} will result in an energy output of 400 kJ m^{-2} day^{-1} and in a NER lower than one, even without considering the energy costs for nutrients and harvesting.[1]

A more favourable situation characterizes algae cultivation in raceway ponds. According to Oswald (1988) power consumption for a large, well-designed, paddle-wheel mixed raceway pond is only 15 kWh ha^{-1} day^{-1} (equivalent to 0.06 W m^{-2}). Weissman et al. (1988) reported a much higher power input (0.25 W m^{-2}) to circulate the culture at a velocity of 20 cm s^{-1} necessary to avoid cell deposition with most algae. Even at the higher consumption rate reported by Weissman et al. (1988) mixing a raceway pond is relatively cheap: only 21.6 kJ m^{-2} day^{-1} when mixing is applied for 24 h a day. The embodied energy of a raceway lined with a 12-year-lifespan PVC membrane has been calculated to be about 30 kJ m^{-2} day^{-1} (Bassi and Tredici, unpublished) and since there is no need for cooling, which is provided, within a certain limit, by evaporation, the total energy cost for algae cultivation in ponds amounts to about 50 kJ m^{-2} day^{-1}. It is to note that these calculations have been done without considering harvesting and medium recycling, which are much more expensive in open ponds than in PBR.

Reducing mixing intensity in the GWP seems possible, but it can reduce productivity in sunny days (Bassi 2010), which is not advisable. The only applicable solution to significantly decrease mixing costs in GWP seems to be reducing the light-path of the panels to reduce the amount of air required to mix the culture without decreasing the superficial gas velocity and thus turbulence. New patent-pending panel designs (e.g. GWP-II), with significantly lower embodied energy and reduced culture thickness (1.5–2.5 cm), are being tested in Florence. These improvements allow to reach a NER close to one. GWP-II, as other low light-path PBR, show other advantages, among which the significant reduction of culture medium to be prepared and handled and a much increased cell concentration, which reduces the energy costs for harvesting.

4 Economics of Algae Biofuel Production

If there is one thing certain with respect to the economics of future commercial-scale algal oil production it is its uncertainty. Since large-scale plants for cultivation of oleaginous algae do not exist, any economic estimate of algae oil production must be based on presumed productivities and costs. In a recent analysis, Darzins et al. (2010) examined three different scenarios for algae-to-biofuel using raceway ponds. In the so called "high oil content and low biomass productivity scenario" a biomass productivity of 10 g m^{-2} day^{-1} with a 40% oil content was assumed, which appears plausible. In fact, at pilot level, an algal lipid productivity of 9 g m^{-2} day^{-1}, corresponding to more than 6 g (oil) m^{-2} day^{-1}, has been demonstrated as feasible (Rodolfi et al. 2009). According to this scenario, the oil cost in large-scale systems (about 40 ML $year^{-1}$) using unlined ponds would be over US\$2 L^{-1} (~ €1.45 L^{-1}) (i.e., double the cost of soybean oil in the US). Bassi and Tredici (unpublished) analyzed the cost of oil-rich biomass production with *Nannochloropis* adopting the two-step process described by Rodolfi et al. (2009). In a 400-ha plant producing annually about 50 t dry biomass per hectare, the cost of algae biomass varied between €2.7 kg^{-1}, when fertilizers and CO_2 are purchased, and €1.1 kg^{-1}, when fertilizers and CO_2 are obtained from wastewaters and flue gas at the sole cost of delivering them to the culture. Only at the lower biomass cost (€1.1 kg^{-1}) it will be possible to produce oil at nearly the cost calculated in the analysis of Darzins et al. (2010), which is, however, not low enough to compete with fossil fuel. Much higher oil productivities, as for example the 20 g (oil) m^{-2} day^{-1} assumed in the "high productivity scenario" by Darzins et al. (2010), and/or much lower cost of resources are necessary to produce biodiesel at a cost comparable to that of petroleum diesel.

The analysis of Darzins et al. (2010) also showed that when instead of ponds, PBR at a capital cost of US\$500,000 ha^{-1} are used to cultivate the algae, the cost of biodiesel increases to more than US\$10 L^{-1} and concluded, in agreement with other published estimates, that in order to compete with raceway ponds, the cost of the PBR should decrease to less than US\$100,000 ha^{-1} (US\$10 m^{-2}).

To produce algal oil at costs not far from the cost of petroleum diesel with current oleaginous algal species, high oil productivities (>10 g m^{-2} day^{-1}) need to be achieved using low-cost "unlined" ponds. However, the suitability of unlined ponds seems dubious since silt re-suspension and interaction of nutrients with the natural substratum will not allow to maintain high growth of the selected strain for as long as necessary. On the other hand, when liners suitable to seal the pond bottom are considered, the cost of production of algal diesel, even in suitable places (e.g. the Australian desert in close proximity to water resources and CO_2 emitters) rises to US\$3–4 L^{-1}, depending on the size of the plant and oil content of the biomass (Darzins et al. 2010).

In conclusion, current available technologies for commercial algae production (either PBR or lined ponds) do not allow yet the competitive production of biodiesel from microalgae, and since ponds seem limited in their possibility

[1] The power input in bubbled panels can be calculated from the following formula: $P_G = V_L \rho_L g U_G$ (Chisti and Moo-Young 1989) where:

P_G is the power input due to aeration (W)

V_L is the culture volume (m^3)

ρ_L is the water density (1,000 kg m^{-3})

g is the gravitational acceleration (9.8 m s^{-2})

U_G is the superficial gas velocity (m s^{-1})

of development, research is mainly focusing on PBR. The interest in PBR is increasing, also promoted by the fact that systems like the Simgae™ and the GWP-II may be built at costs not far from, or even lower than, those of lined ponds. However, it is worth noting that operating costs, more than capital costs, make algae biomass (and oil) production in PBR too expensive.

5 Conclusions

World commercial production of microalgae is limited to about 20,000 t year^{-1}. Only few hundred tonnes are produced in closed photobioreactors. There is essentially one reason for preferring open ponds or lagoons of low productivity for algae cultivation, and this is cost. At large scale, PBR are more expensive to build and operate than raceways ponds, which are thus used in the majority of commercial plants.

By providing a closed, more controllable environment and, in many cases, by light dilution, PBR may achieve a higher efficiency of solar energy conversion compared to open systems. However, rarely these advantages translate into a significantly higher areal productivity and compensate the higher cost of PBR. It is true that, because they are closed and have a higher S/V ratio, PBR save water by avoiding evaporation and produce more biomass per liter. However, water savings are more than offset by the need to cool the culture, which in open ponds is obtained at no cost thanks to evaporation, and not always the higher volumetric productivity of a high S/V ratio PBR leads to higher areal productivities. Light dilution in PBR has been shown to reduce photosaturation and photoinhibition and a significant increase of areal productivity has been actually obtained by using vertical reactors on which sunlight is spread, and thus diluted, on a large surface area. But, the drawbacks of a high reactor-area to ground-area ratio (typically between two and ten) are self evident: it requires large reactor transparent surfaces, and this significantly increases capital and operating costs. The real advantage of PBR is that by limiting the risk of contamination they allow more species to be cultivated and that, thanks to their shorter light-path, they achieve higher cell concentrations with significant savings in harvesting and medium preparation and handling.

New PBR designs are emerging, like the Simgae™, the GWP-II and the ProviAPT, that show construction costs similar to or lower than those of lined ponds. However, a low construction cost is not enough to make these systems competitive for large-scale production of algae biomass. The raceway pond is a very efficient culture system that, except in humid climates, does not require cooling and in which sufficient turbulence can be generated at an energy expenditure of less than 5% of the energy stored in the biomass. On the contrary, PBR require energy inputs for mixing and cooling that, together with the reactor embodied energy, may surpass the energy content of the biomass.

Growing microalgae in open ponds is much cheaper. Growing algae in PBR is generally safer and more reliable. It is thus very likely that an industrial plant for cost-effective production of biofuel from microalgae will adopt a strategy that combines both PBR, in which active inocula of the selected species are produced, and ponds for bulk cultivation.

When a biofuel is the target product, the most important issue is the cost of the biomass which will be processed to yield the fuel. The current cost of algal biomass production (US$5 kg^{-1} being the lowest possible with available technologies) exceeds by 20 times that required for economic fuel production (about US$0.25 kg^{-1} prior to conversion to biofuel). Some recent estimates (see for example that of Darzins et al. 2010) confirm that productivities will have to increase and costs decrease significantly to achieve this ambitious goal.

The strategy to decrease the cost of algae biomass is undoubtedly complex. The key issue is strain selection, that should be based on strain productivity, robustness, oil (or carbohydrate) content, harvestability and extractability. The candidate microalga must then be thoroughly studied at a significant large scale outdoors to maximize its productivity in terms of biomass and desired component (e.g., TAGs for biodiesel, sugars for ethanol). Low-cost reactors with automated process control should be adopted for inexpensive production of inocula, and low-cost, lined, large-scale ponds must be designed to carry out the accumulation of the "energetic" compound. It will be fundamental the close proximity of the plant to water resources and that CO_2 is provided "free of charge" at the battery limits of the production facility. When available, and compatible with reliable growth and high productivity of the selected strain, wastewaters should be used as nutrient sources. Also important will be that value is generated from the residual biomass (e.g., used for animal feed).

In conclusion, despite its "appealing" potential, investors should be aware that the algal biofuel technology is not ready yet, a reasonable projection for the establishment of an economically viable process being 10–15 years. The high lipid or carbohydrate productivity per land area and the lack of competition for freshwater and arable land amply justify, however, the renewed interest of researchers and the ongoing large investments in algae biofuel.

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