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Vacuum Air-lift Bioreactor for Microalgae Production

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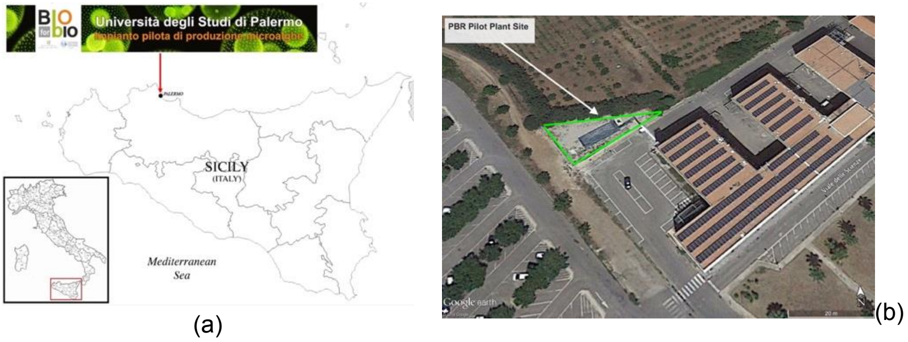
Microalgae production is receiving an increasing interest both by research institutions and commercial companies (Di Caprio *et al*., 2016). This is due to the growing consciousness of the need to move towards renewable, sustainable feedstoks for commodities production (Wang *et al*., 2012). However, process development at industrial scale, either based on open or closed photobioreactors, still is in a rather early stage and there is room for further development (Morweiser *et al*., 2010), especially aimed at reducing process costs.

In this work an innovative low-cost technology for microalgae production, currently under development at Palermo University, is described. The main ways through which the goal of costs containment is pursued are (i) the adoption of thin walled transparent tubing for the photo bioreactor, and (ii) an evacuated-head air-lift system. To the aim of providing a proof-of-concept of these ideas, a 500-liter pilot plant was built. This is presently being operated in semi-continuous mode under solar irradiation and external climatic conditions.

1. Methodology

The innovative Photo-Bio-Reactor (PBR) pilot system was built within campus of Palermo University (Italy), as shown in Figure 1. This location is ideal for microalgae growth, as it s located in the south of the Mediterranean area, the climate is warm, and on average there are no temperature values below 15 °C throughout the year (Thangavel *et al*., 2015).



(a) (b)

Figure 1: (a) Location of the PBR pilot plant within the Palermo University Campus; (b) Satellite image of the pilot plant location (space information comes from Google Maps® courtesy).

The development of a microalgae production plant involves the study of many strongly related operating parameters, such as incident light, plant dimensions, temperature, pH, flow rates, O_2 concentrations, etc.

1.1 Pilot Plant Conceptual Design

Figure 2 shows the conceptual pilot plant scheme developed for microalgae cultivation.

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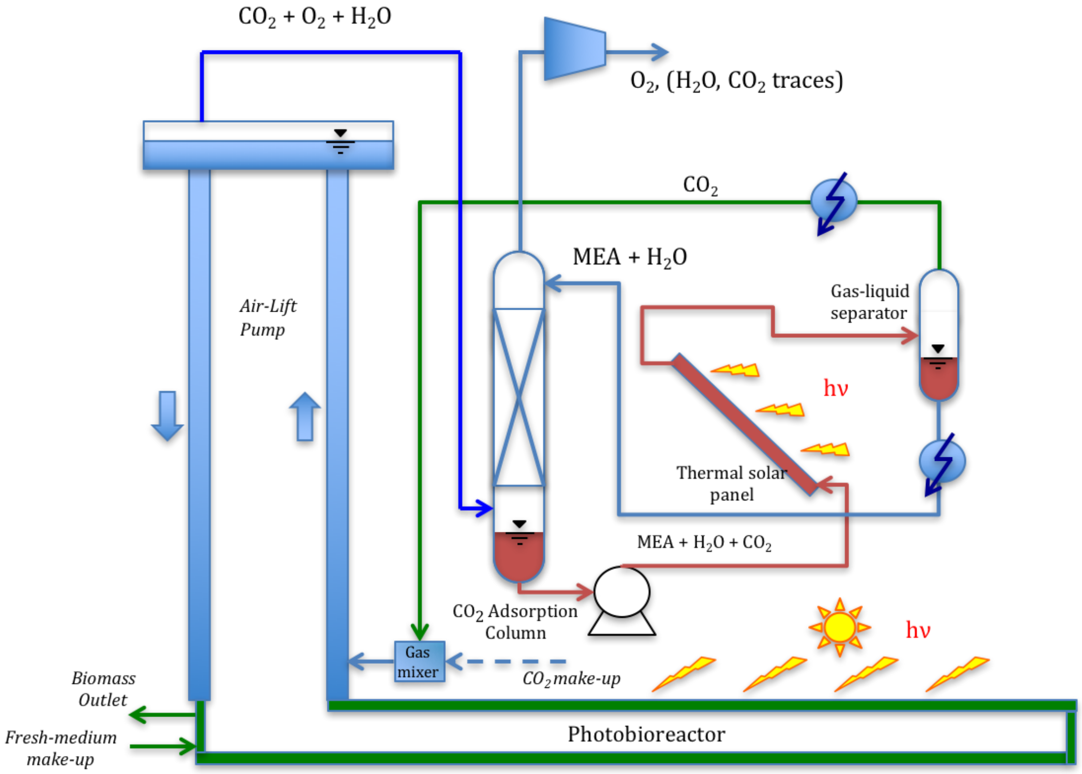


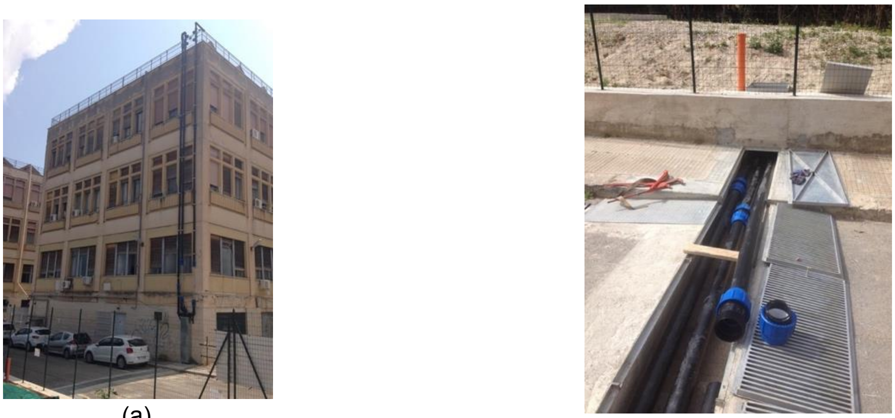
Figure 2: BIO4BIO Project - Conceptual pilot plant scheme for microalgae cultivation.

As it can be seen, when compared to typical microalgae cultivation plants, in the present case there are two significant innovations: the top-evacuated Air-Lift system and the CO_2 recovery/recycle section through mono-ethanolamine (MEA) absorption/desorption. Plant sections may be summarized as follows:

- *Photobioreactor section*: photobioreactor pipes are made of horizontal transparent pipes exposed to sunlight (outdoor system). The pipe construction material should be low-cost, characterized by high solar radiation transparency and sufficient UV resistance and, depending on their thickness and rigidity, may be either laid down on the ground (simply flattened and covered by a low-cost plastic protection cloth), or suspended on suitable pipe-racks (Marotta *et. al*., 2017);
- *External loop Air-Lift section:* the main components are the riser, the downcomer and the degaser. In the riser section, the medium coming from the photobioreactor ascends together with a CO_2 gas stream injected through a suitable sparger. The separation between gas and liquid phase takes place in the degaser section. The gas-freed liquid phase descends *via* the downcomer and feeds the photobioreactor tubes.
- *Withdrawal/Make-Up section:* at the downcomer bottom a portion of the circulating microalgae suspension is withdrawn as a product stream, while fresh medium is fed to replace the liquid phase withdrawn.
- *CO_2 recovery/recycle section:* this section comprises a chemical absorption column, a solar heater and a desorption flash separator. The low pressure gas phase coming from the air-lift degaser is fed at the bottom of the absorption packed tower, in which a mono-ethanolamine (MEA) water solution is also fed at the top. During the countercurrent contact with the liquid phase, the gas stream is freed from CO_2 and from part of the water vapour, which are absorbed by the cold liquid phase. Oxygen reaches the tower top, where it is extracted by a vacuum pump. The spent liquid solution is sent to solar thermal panels, where it is heated to about 100°C: at this temperature the absorbed CO_2 is released at a pressure sufficient for recycling it to the airlift, after cooling. The hot regenerated *MEA-H_2O* solution is cooled-down and sent to the CO_2 absorption tower.
- *O_2 rich stream:* the almost pure oxygen stream obtained at the exit of the vacuum pump may be used as it is, for processes requiring O_2 rich streams (e.g. oxy-gasification processes, incineration of toxic wastes, fish farming etc.), or further purified and compressed for medical applications. It is to be regarded in all respects as a microalgae co-product, being in the range of 1 kg of O_2 / kg of algae biomass produced.

1.2 Experimental site and apparatus

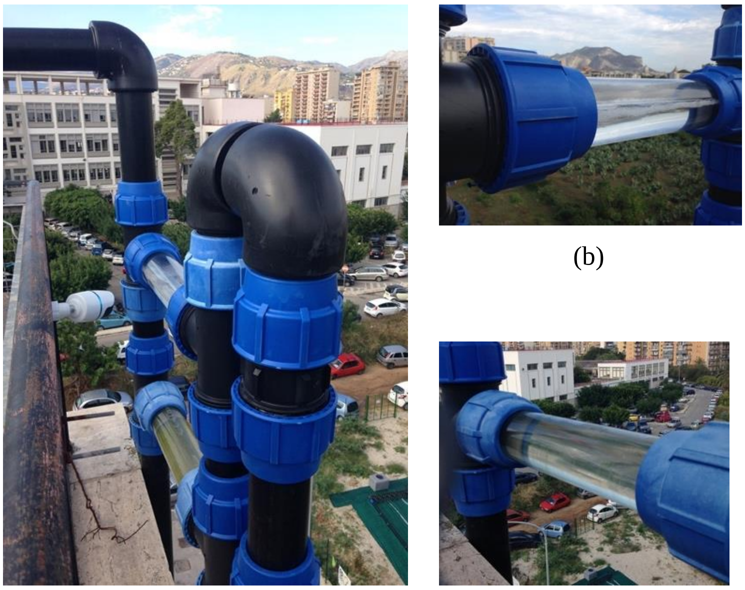
The 20 meters high Air-Lift section was built near the photobiorectore land area and was supported by the walls of a nearby university campus building and is shown in Figure 3-a. Is is connected to the photobioreaction section by means of a trail carved along the street road, as shown in Figure 3-b.


(a)

(b)

Figure 3: (a) Evacuated-head Air-Lift mounted on the side of Building 6, in front of pilot area; (b) Trail carved along the street road to connect the evacuated-head Air-Lift to the photobioreaction section.

All main pipelines are in polypropylene (PP). Photobioreaction section is transparent with thin polyethylene film pipes *60 mm* in internal diameter, able to capture light radiation for microalgae growth. Table 1 shows the main pilot plant sizes.


(b)

(a)

(c)

Figure 4: (a) Dual transparent Degaser with (b) free surface in the highest section and (c) lower section completely full.

Regarding the Air-Lift Unit, it is worth noting that the degaser section consists of two horizontal parallel pipes, one above the other, of the same diameter as the riser and downcomers, simply connected to these by standard T junctions. Notably this design was found to effectively sort out two different problems observed when using a single connection: (i) the strong dependence of liquid circulation rate on the liquid height in the degaser and (ii) significan bubble entrainment in the downcomer section, due to the relatively high velocities in the partially filled single degaser system. Clearly both problems might have been addressed also by significantly enlarging the cross section of the single degaser, but at the cost of difficulties in finding suitable standard fittings and consequently the need of resorting to specially bult connections.

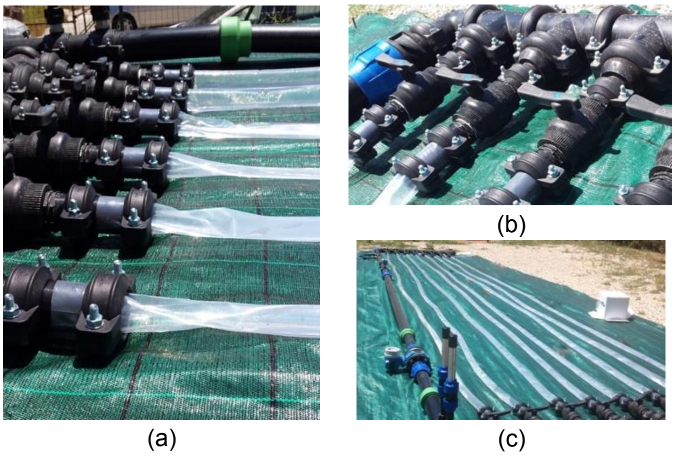
Table 1: Characteristics and size of the PBR pilot plant.

Section	ID [m]	Length [m]	Volume [L]
Riser	0.08	18	~ 90
Downcomer	0.08	18	~ 90
PBR line connection	0.08	17	~ 84
Degaser	0.10	0.80	~ 6
PBR	0.06	81	~ 230
		Total Volume [L]	~ 500

1.3 PBR section

Thin tubing made in low density polyethylene (LDPE) were used. The photobioreactor section consisted of eight horizontal 10 m tubes connected in parallel as shown in Figure 6. It is worth noting that in this PBR Unit, VICTAULIC® grooved piping, fittings and couplings were chosen, always supplied by *Plastica Alfa*, for easy replacement and modification of the entire section. In order to enable or disable individual parallel photobioreactors, manual PP ball valves were inserted in the inlet and outlet manifold.

One centrifugal pump (Calpeda NM40/16B/B) was used to supply fresh water and inoculum to the pilot plant, while a vacuum pump (Edwards ES65) was used to perform the gas stripping from the degaser.


(b)

(a)

(c)

Figure 6: Photobioreactor Unit with LDPE film tubes.

The Centrifugal pump is only activated at the beginning of microalgae growth cycle and it has a prevalence able to fill up the pilot plant in a few minutes. The measuring instrumentation is constituted by pH/temperature sensors/transmitters (*WTW Sensolyt 700 IQ*), oxygen sensors/transmitters (*WTW FDO 700 IQ*), turbidity sensor/transmitter (*WTW Visoturb 700 IQ*), and digital pressure gauge (*EH Cerabar S PMC 71*) for both inlet/outlet PBR Unit section. An additional digital pressure gauge is installed at the top of Air-Lift, and a CO_2 sensor/transmitter (*Mettler Toledo ISM INPRO 5000i*), is installed near PBR inlet section. The inlet/outlet flow rate of the growth medium was measured by magnetic flowmeters (*EH Promag 10L*).

2. Preliminary Results

At present the CO_2 recovery section is still under construction. For the time being, only hydrodynamics tests were performed by feeding an air stream to the system in order to evaluate system fluid dynamics functionality. For this reason, a mathematical model able to predict system fluid–dynamics was developed and compared with preliminary experimental results.

The model accounts for the volume increase by gas bubbles due to decreasing absolute pressure while rising upwards. The consequent increase of gas volume fraction implies an acceleration of the liquid phase, also fully accounted for in the liquid phase momentum balance. Further details may be found in the PhD thesis of Marotta (Marotta, 2016).

In Figure 7 the experimental liquid flowrate (Q_L) observed at various air flow rates is reported both for the case of atmospheric top pressure (diamonds) and for the head evacuated system (black circles).

As it can be seen, vacuum application to the airlift top enhances the liquid circulation performance for the same inlet gas flow rate, by a minimum of 8% up to a maximum of 17%. It is worth noting that higher inlet gas flow rate values were not considered in order to avoid a too large gas entrainment in the downcomer section.

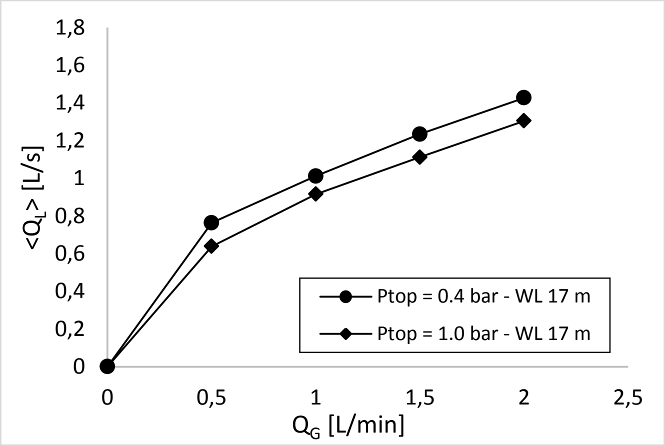


Figure 7: Pilot Plant experimental results by activating (Air-Lift head evacuated) and deactivating (atmospheric pressure) vacuum pump, with a water level (WL) of 17 meters.

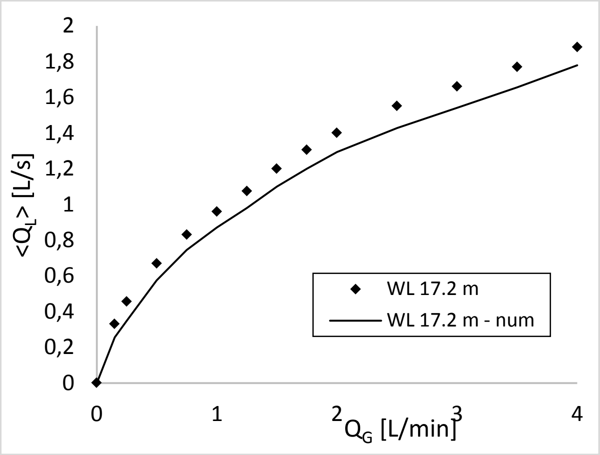


Figure 8: Comparison between Pilot Plant experimental- and numerical results, with a water level (WL) of 17.2 meters.

Experimental liquid flow circulation results were also compared with numerical results in Figs. 8 and 9. As it can be seen, both for the case of the head evacuated air lift and for the athmospheric prssure air – lift, numerical results are found to be in good agreement with experiment, with percentage standard deviations between 3% and 7%, depending on the inlet gas flow rate.

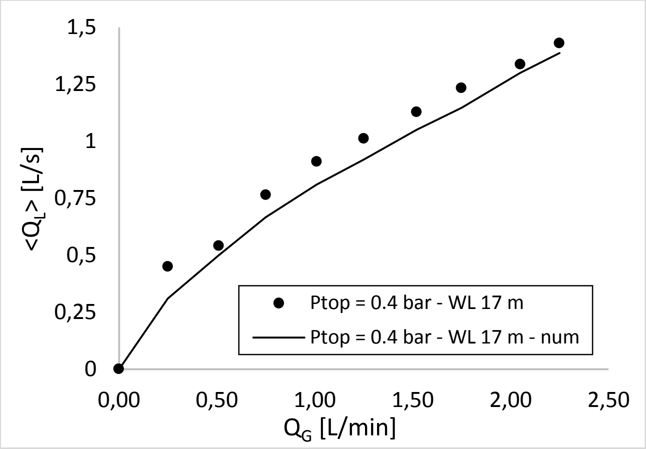


Figure 9: Comparison between Pilot Plant experimental results and numerical results by activating (Air-Lift head evacuated) vacuum pump, with a water level (WL) of 17 meters.

3. Conclusions and future perspectives

A 500-liter pilot plant was built within the Palermo University Campus. This is presently being operated in semi-continuous mode under solar irradiation and external climatic conditions. The relevant air-lift deployed is about 20 meters high and has an internal diameter of 8 centimetres. A novel double-degaser in the air-lift head was found to provide good gas-liquid separation. Air, or an air-CO_2 mixture, is presently sparged at the riser bottom, but pure CO_2 sparging is planned to be tested. This last, in conjunction with the evacuated air-lift head should also allow the co-production of nearly pure Oxygen from the same plant. Preliminary results on system fluid-dynamics showed that the evacuated head improves liquid circulation, as expected. A mathematical model able to predict liquid circulation rates was also devised and found to compare well with experimental results.

Acknowledgements

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