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A Novel Photo-bioreactor Application for Microalgae Production as a Shading System in Buildings

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A novel photo-bioreactor application for microalgae production as a shading system in buildings

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Abstract

The optical performances of plastic bag photo-bioreactors for microalgae production as shading systems for windows were assessed. The micro-algal growth rate and the light transmittance of prototypes were monitored in a photo-incubator and in a real room. Daylight in the room with algae and the energy demand for lighting ED_l were then simulated using Daysim and compared to the case of a traditional venetian blind, for two different Italian sites (Turin, Palermo) and 3 orientations (south, west, north). It was found that the algae-system resulted in increased daylight level and glare and in decreased ED_l.

1. Introduction

This paper presents a feasibility study on photo-bio reactors (PBRs) used as vertical static photo-bio screens (PBSs) in buildings. PBSs integrate the ability of green microalgae culture to shield direct sunlight, i.e. to selectively absorb the red radiation (wavelength = 0.6-0.7 μm), with the capability to both bio-sequestrate CO_2 from the ambient air and to generate biomass contzaining bioactive compounds. The PBSs tested in this work are thin, modular, disposable, plastic bags and they consist of small transparent cubicles, of different shape, containing the culture of microalgae and the nutrient supply. Cubicles are embedded in a flexible polymeric matrix permeable to CO_2. Several

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factors provide the PBSs with a special appeal from the sustainability point of view: the carbon dioxide bio-sequestration, the production of biomass in indoor cultivation, the enhancement of indoor environmental quality IAQ and their recyclability. IAQ increases since the indoor air quality improves (due to the sequestration of CO_2 from the indoor environment), the direct sunlight is screened and scattered and the visual appeal of the green surface improves the psychological well-being of the occupants. In this study, five different PBS prototypes were built, measured in laboratory and installed in a real sample test room (3.9 m x 2.4 m; 3.5 m high): they were different for layout, size, shape and surface area/volume ratio of the cubicles, as well as for the presence/absence of mixing by bubbling air. In detail, the following parameters were determined: growth rate of micro-algal cultures, through optical density (OD) measurements; light transmittance LT through bioreactors, by measurements in-the-field on the prototypes as well as through Radiance simulations following a procedure developed in a previous work [1]; amount of daylight in the room and the related energy demand for lighting ED_l, through Daysim simulations.

The impact of electric light or of daylight on algae-systems was addressed in many studies [2-9]. These were mainly focused on aspects such as the biomass productivity, cell growth, CO_2 fixation efficiency or the efficiency of the production rate for different light sources, latitudes, orientation, shading effects, in both indoor and outdoor cultivating systems and by designing special PBRs to increase the microalgae growth rate and the biomass productivity. Very few studies analyzed the LT of algae-based systems, and through a qualitative approach only. For instance Kim et al. [10] described a system which was applied to a real office building in Seoul: they paid attention to aesthetical issues, to the possibility to guarantee a view to the outside for the occupants and to offer good energy and structure performance as well. The optical properties of the system, though, were not measured. In this context, the determination of LT of PBSs, visual comfort and the ED_l is one of the novelty issues addressed in this paper, as well as the rigorous comparison between different prototypes of PBSs so as to come up with the layout effectively arranged, able to assure a suitable solution in terms of microalgae growth rate at different ambient conditions.

2. Experimental procedure

2.1. Reactor design and preparation

The following parameters were considered for PBSs design: cost, volume, surface area/volume ratio, and thickness of reactor. Different types of PBS were selected to be tested, with and without mixing (Table 1); more precisely microalgae were cultivated in SCC and SCCO in static conditions or with air injection. SCC was the first one used for microalgae culture due to its low cost and easy availability. The bag consists of two LDPE sheets (0.05 mm thick) thermally welded so as to create circular cubicles with square packing (fig. 1a).

In order to compare the performances of PBSs, different layout were selected (see Fig. 1 and Table 1 for codes and description). SCR (fig. 1b), SCCO and ASCCO (fig. 1c) prototypes were prepared by thermally welding two LDPE sheets along a defined drawing: rectangular cubicles (SCR) or circular cubicles with high-density hexagonal packing (SCCO and ASCCO). LDPE was chosen because of its good permeability to CO_2 (permeability coefficient = 106 cm^3 mm/m^2 day atm [11]), thermal weldability, recyclability and absence of wall growth and fouling.

To avoid settling of the microalgae, relatively inexpensive mixing inside ASCC and ASCCO (fig. 1c) was promoted through air bubbling which caused agitation and distribution of the cells inside cubicles. Cubicles were interconnected each other and crossed by three vertical PTFE tubes (Φ_{int} = 4 mm) connected to a membrane pump aerator. Aeration rate was measured in liters of air per liters of cubicles per min (vvm). A video camera (set at 7000 frames per second) was used to capture the dynamics of the air bubbles and their mean size (1–5 mm). The maximum thickness, measured at the center of all cubicles filled with cultures was lower than 20 mm (table 1). Interconnection between cubicles allowed free circulation of fluid, microalgae and gas bubbles.

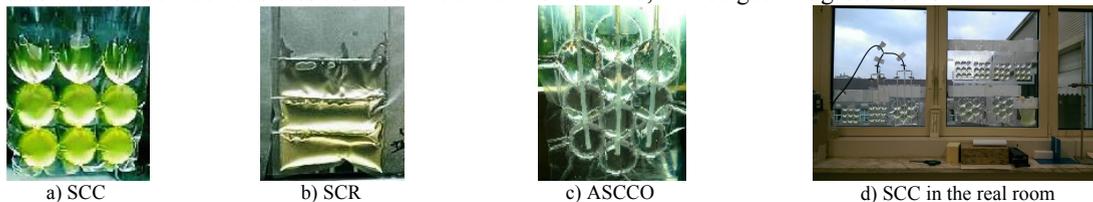a) SCC   b) SCR   c) ASCCO   d) SCC in the real room

Fig. 1. PBSs: a) SCC circular cubicles/square packing; b) SCR rectangular cubicles; c) ASCCO aerated circular cubicles/hexagonal packing.

Table 1. Characteristics of PBSs.

Code and description	Bag			Cubicles				
	Size (mm)	Culture volume (ml)	Wall thick. (mm)	Size (mm)	Culture volume (ml)	Max. thick. (mm)	Surface area/vol. (mm⁻¹)	Aeration rate (vvm)
SCC *disposable ice bag: 9 circular cubicles with square packing*	150x150	120	0.05	$\Phi = 45$	13	17.5	0.12x2	-
ASCC *aerated disposable ice bag: 9 circular cubicles with square packing*	150x150	120	0.05	$\Phi = 45$	13	17.5	0.12x2	0.4
SCR *3 rectangular cubicles arranged in three horizontal lines*	150x150	120	0.125	35x135	40	19.5	0.09x2	-
SCCO *10 circular cubicles with hexagonal packing*	300x240	250	0.1	$\Phi = 65$	25	18.5	0.13x2	-
ASCCO *10 aerated circular cubicles with hexagonal packing*	300x240	250	0.1	$\Phi = 65$	25	18.5	0.13x2	0.2

2.2. Microalgae culture

The microorganism utilized in this work is *Scenedesmus obliquus* CCAP 276/38, a freshwater microalga. It was maintained at +4°C on a Proteose-Peptone solid medium (PP agar), containing (per litre) 0.02 g of $MgSO_4 \cdot 7H_2O$, 0.02 g of K_2HPO_4, 0.2 g of KNO_3, 1 g of Proteose-Peptone, and 20 g of agar. PP agar was inoculated and incubated for 15 days at room temperature and natural alternation of dark/light. All the cultures were settled in liquid media. A standardized inoculum of 10% v/v was provided for each cultural condition tested.

The Proteose-Peptone liquid medium (PP-M),with the same composition as that of PP agar, was used for all the pre-cultures (200 ml) prepared in EFPs, i.e. 500 ml Erlenmeyer flasks placed inside a photo-incubator (Photosynthetic Light bank, Innova 43R/44R, with 15 W lamps at a wavelength of 660 nm), in agitated conditions (120 rpm), at 20°C, with artificial dark/light cycles (12/12 hrs), i.e. standard culture conditions, for a total duration of 72 hours.

The first set of experiments was performed during 21 days, from July 2 through 22, 2015, using the same medium as that of the pre-cultures. The aim of this preliminary tests was to evaluate the possibility to cultivate *S. obliquus* in plastic bags of different geometry and to monitor the micro-algal growth trend in a sample room at a constant indoor environmental temperature (the room was air conditioned), with natural light/dark (L/D) cycles, and without stirring. For this purpose cultures (120 ml) were prepared in three SCCs and two SCR bags. A simultaneous control was realized cultivating *S. obliquus* for 21 days in three EFPs (200 ml) maintained in standard culture conditions.

A second set of experiments was carried out to evaluate the performances of the PBSs with circular geometry, having both square packing and hexagonal packing, with and without mixing. A series of four bags of SCC and two bags of SCCO types was tested during 21 days in the real room, from October 14 through November 3. One bag of ASCC and one of ASCCO with air bubbling mixing was tested during 10 days, from October 14 through 23. In order to evaluate the possibility to cultivate *S. obliquus* in a liquid medium containing a less expensive inorganic carbon source, the proteose-peptone was replaced with sodium bicarbonate ($NaHCO_3$), having an initial concentration of 50 mM. In the sodium bicarbonate liquid medium (NaB-M50) the other components were the same as those of PP-M one. Two EFP cultures (200 ml) were used for the simultaneous cultivation of *S. obliquus* in controlled conditions in NaB-M50 medium.

Spectrophotometrical determinations at 620 nm wavelengths (OD_{620}) were periodically conducted to control micro-algal growth in the cultural medium using a HP 8452A diode array spectrophotometer.

On the basis of the absorbance values at 620 nm the maximum micro-algal growth rate (μ_{max}) was calculated as:

$$\mu_{max} = \log_{10}(OD_t/OD_0)/\Delta t \qquad (1)$$

where OD_0 is the initial OD_{620}, OD_t the OD_{620} at the selected time and Δt the time interval (in hours).

2.3. Light transmittance LT

The LT was measured in the field using the equipment installed in the real room located in Politecnico, Turin. Two types of data were acquired for the purpose: illuminance and luminance data.

Illuminance values were monitored for periods of one week for 5 weeks (October 12-16, 19-23 and 26-30, 2015; November 2-6 and 9-13, 2015), using a set of 6 data-loggers: 2 of them were positioned immediately after the glazing, while other 4 immediately after the algae-systems (which in turn were hang to the interior face of the glazing). Illuminances were acquired with a time-step of 5 minutes: per each time-step, the average illuminance of the 2 loggers positioned after the glazing was calculated and the same for the 4 loggers positioned after the glazing with the algae cultures. The LT was then calculated through the equation (2a). Besides, a series of luminance measurements were taken using an Image Luminance Measuring Device (Techno-Team LMK 98-3): for a limited number of time-steps, a luminance map was captured of the whole glazing. This is a digital HDR image, calibrated in such a way that each pixel gives a luminance value as output. Two maps were taken, one in the presence and one in the absence of the algae-system. The average luminance of the algae area was determined from the two images and the LT value was then calculated through equation (2b):

$$LT_E = \frac{\text{mean E of loggers after the glazing+algae}}{\text{average E of loggers after the glazing system}} \qquad LT_L = \frac{\text{mean L of the area covered by the glazing+algae}}{\text{mean L of the same area withough the algae}} \qquad (2, a\text{-}b)$$

2.4. IEQ (visual comfort) and energy saving simulations

An analysis of the IEQ, in terms of visual comfort perceived by the occupants, and of the ED_l which may get reduced by using SCC as PBS was carried out through Daysim and Radiance simulations. The room used for the monitoring activities was modelled for this purpose. The room has the following photometric and lighting system characteristics: a double pane selective glazing (LT = 72%), equipped with the algae cultures (global LT of the package = 55%); LR values of walls, floor and ceiling: 60%, 30% and 70%, respectively; room orientation: south; target illuminance over the work plane, E_{wp}: 500 lx and 300 lx; lighting power density (LPD): 10 W/m^2 and 6 W/m^2 (for E_{wp} = 500 lx and E_{wp} = 300 lx, respectively); control system for electric lighting: a photo-dimming sensor (parasitic power due to stand-by of the sensors = 0.12 W/m^2; luminaires' ballasts = 10% of the luminaire power).

The following features of the room were changed to create different cases for which to calculate and to compare the daylight amount and the corresponding energy demand for lighting:
- site: beside Turin, northern Italy (45.1°N), the room was also located in Palermo, southern Italy (38.3°N), that is a site with a highly different daylight availability and shading requirements
- orientation: the room was assumed to be facing south (real case), west and north (different sunlight availability)
- glazing system: the real case (glazing + algae, LT = 55%) was compared to the case of the same glazing coupled with a traditional venetian blind to shade the direct sun. The blind has a LT of 25% when it is pulled down. According to the Daysim algorithms, the blind is controlled by the occupants) based on two set-points: a) an *irradiance set-point*, i.e. the blind is pulled down whenever during an annual simulation any point of the work plane is hit by an irradiance over 50 W/m^2 (a typical condition which causes thermal discomfort for the occupants); b) a glare set-point (*Daylight Glare Probability DGP-set-point*), i.e. the blind is pulled down whenever during an annual simulation an intolerable glare is experienced by an occupant (DGP > 0.45 [12-13]).

The amount of daylight in the room was quantified through the average daylight factor (DF_m) over the work plane (under an overcast sky) and through some climate-based daylight metrics CBDM: these latter account for both sunlight and skylight dynamically entering an indoor room throughout a year for the considered site [14-15]. The following CBDM were used: spatial Daylight Autonomy ($sDA_{300/50\%}$) [16] and Useful Daylight Illuminance [17]. The $sDA_{300/50\%}$ is defined as "the percent of an analyzed area that meets a minimum daylight E of 300 lx for 50% of the operating hours per year", while the UDI metric refers to E threshold (E<100 lx, i.e. a too scarce daylight, which pushes the users to switch electric lights on; 100 lx<E<3000 lx, i.e. an ideal illuminance level for users; E>3000 lx, i.e. potentially excessive daylight, resulting in discomfort for the occupants). Both metrics were included in recent technical recommendations: $sDA_{300/50\%} \geqslant 55\%$ for a 'nominally accepted daylight sufficiency' and $sDA_{300/50\%} \geqslant 75\%$ for a 'preferred daylight sufficiency' [16,18]; average $UDI_{100\text{-}3000} > 80\%$ [19].

The visual comfort in the considered space was specifically investigated by calculating the annual DGP value [12]. The user was assumed with a constant view toward the window: this is not a realistic case, but it was done to have a worst-case condition under which to compare the two considered technologies. In a more realistic scenario, the users would tend to adapt themselves to reduce the discomfort perceived, changing their direction of view in response to the ambient conditions (concept of 'adaptive zone', introduced by Jakubiek and Reinhart [20]).

The ED$_l$ was calculated in [kWh/m^{2}yr], as commonly done for other energy demands (for cooling, heating).

The DF and CBDM annual profiles were calculated using Daysim, while the annual DGP profile using Evalglare, a simulation tool included in the Radiance package. Both Daysim and Radiance were managed using DIVA-for-Rhino. Besides, a program was specifically written in Python to manage and process the results. All the annual analyses were performed using a time-step of an hour and an occupancy profile Monday through Friday, from 8:30 am 'till 6.30 pm (without any lunch breaks).

3. Results

3.1. Influence of PBS design, C-source and cultural parameters on the growth of S. obliquus.

The first set of experiments was performed during 21 days, from July 2 through 22, in order to evaluate the possibility to cultivate *S. obliquus* in PBSs, and to monitor the micro-algal growth trend in a sample room at indoor environmental temperature, with natural light/dark (L/D) cycles, and without agitation. The growth curves for the PBSs were compared to that of a cultivation carried out in Erlenmeyer flasks kept inside a photo-incubator (EFP) under controlled conditions as described in section 2.2. Rectangular (SCR) and circular (SCC) geometries of PBS cubicles were tested in the PP-M medium, the volume of the culture was 120 ml for each device. The obtained results are reported in fig. 2a. The red line (referred to the vertical axis on the right-hand) represents the temperature trend measured during 21 days immediately after the PBSs hanged over the interior face of the sample room glazing.
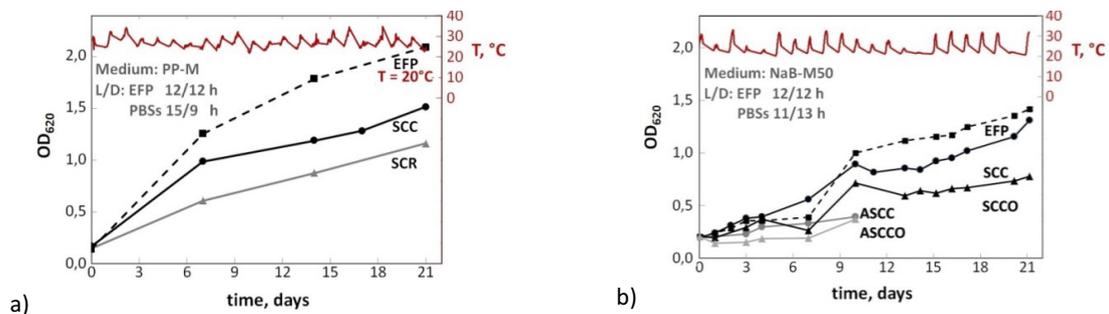

Fig. 2. Optical density readings at 620 nm (maximum difference of repeated tests < 15%): a) comparison between SCC, SCR and EFP cultures in PP-M medium; b) comparison between SCC, SCCO, ASCC, ASCCO and EFP cultures in NaB-M50 medium.

The results show the possibility to cultivate the microalga for a period of 21 days in EFPs and PBSs in a range of temperature varying between 20°C and 35°C and in the PP medium, containing an organic C-source. The final OD$_{620}$ value (maximum difference of repeated tests < 15%) referred to both SCCs (1.5) and SCRs (1.2) is lower when compared to that related to the growth into the agitated EFPs (2.1), maintained in controlled conditions. Between the two type of PBS, the SCC is the eligible one: its OD$_{620}$ values are higher than those observed for SCR. Based on these results, the circular geometry of the cubicles was adopted for all the following experiments.

Once the possibility to cultivate *S. obliquus* was proven, another improvement was the use of circular cubicles arranged with a high density hexagonal packing (SCCO). This device allowed to cultivate the microalga in a higher medium volume (250 ml), nearly doubled respect to that of the SCC type. Tests were performed during 21 days, from October 14 to November 3. The growth curves (fig. 2b) for SCC and SCCO were compared to that of cultures carried out into the EFPs under controlled conditions. Moreover, the growth of *S. obliquus* was carried out in the NaB-M50 liquid medium, containing NaHCO$_3$ 50 mmol/l, a less expensive inorganic carbon source. Until the 7th day, the trend of SCCs and SCCOs growth curves was similar to that of EFPs, after that growth rate of EFPs was higher than those of PBS ones. Nevertheless, during all the experiment time, OD$_{620}$ values were always higher for SCCs with respect to those of SCCO. Probably, the higher surface area/volume ratio (0.24 mm^{-1}) and the lower thickness of SCC cubicles (17.5 mm), i.e. the reduced light path, increased local irradiance and promoted microalgae growth [21] [22].The final OD$_{620}$ values at 21 days for EFPs, SCCs and SCCOs were 1.4, 1.3 and 0.8 respectively (maximum difference of repeated tests < 15%), in a range of temperature between 20°C and 35°C. NaB-M50

medium, containing the $NaHCO_3$ as inorganic carbon source, allows *S. obliquus* to be cultivated in SCC and SCCO photo-bioreactors with a similar behaviour to that obtained with the organic carbon source (PP-M medium).

For SCC and SCCO devices the effect of mixing by air injection was also tested during 10 days. Mixing could be necessary to prevent microalgae sedimentation and aggregate formation that could decrease mass transfer rates of the nutrients to the cells [23] and prevent their homogeneous suspension. Furthermore, a self-shading effect could take place due to the combination of photon absorption and cell scattering phenomena [21]. The growth curves for the aerated PBSs (ASCC and ASCCO) are also reported in fig. 2b. Mixing, operated by air bubbling, seems to have an inhibition effect on the cell growth both for ASCC and ASCCO. Despite rising bubbles increase the local irradiance inside the photo-bioreactor scattering light in the forward direction [24], turbulence can stress microalgae due to the occurrence of hydrodynamic forces [23].

The maximum growth rate values (μ_{max}) obtained in EFP and PBS devices (table 2) confirm the previous exposed results. SCC with organic (PP-M) and inorganic carbon source (NaB-M50) showed μ_{max} values (0.009 and 0.006 h^{-1}, respectively) very similar to those of EFP ones (0.01 and 0.007 h^{-1}, respectively). SCCO with NaB-M50 medium showed lower optical density and μ_{max} values (0.005 h^{-1}) respect to the SCC. Finally, the lowest μ_{max} values were obtained for ASCC and ASCCO devices (0.002 h^{-1}).

Table 2. Maximum growth rate values (μ_{max}).

PBS	Medium	ΔT, °C	L/D, hrs	μ_{max}	PBS	Medium	ΔT, °C	L/D, hrs	μ_{max}
EFP	PP-M	20	12/12	0.010	SCCO	NaB-M50	20-35	11/13	0.005
EFP	NaB-M50	20	12/12	0.007	ASCC	NaB-M50	20-35	11/13	0.002
SCC	PP-M	20-35	15/9	0.009	ASCCO	NaB-M50	20-35	11/13	0.002
SCC	NaB-M50	20-35	11/13	0.006					

In short, the following main considerations were drawn:
1. Circular geometry of cubicles performs better than the rectangular one.
2. SCC with square packing of cubicles performs better than SCCO with hexagonal high density packing
3. Mixing operated by air bubbling is not necessary and could be self-defeating
4. PP-M medium, containing an organic carbon source, performs better than NaB-M50, containing an inorganic carbon source. Nevertheless, NaB-M50 medium is cheaper and allows *S. obliquus* to be cultivated in SCCs with a similar behaviour to that obtained with PP-M.

3.2. Light transmittance LT

Figures 3 and 4 summarize the results which were found for the LT from E and L measurements.

The most outstanding consideration is that the LT value is highly changing with time, with values which overcome the theoretical maximum value of 1. This is due to the different positions of the sun in the sky and to the refraction and scattering effects produced by the material the PBS is made of as well as by the algal cells. The structure of PBS consists of cubicles which are biconvex lenses: as a consequence of the direction of the incoming solar rays, this structure may enhance the refraction and internal reflection of solar rays, with a consequent increase in the amount of light transmitted along a given direction in the room. This effect can be observed through the luminance maps: as shown in fig. 3, particularly for areas 1, 2 and 7, the luminance values are increased in correspondence of the algae and are higher than the corresponding luminance values in the absence of the algae system. As a result, for these area and for that specific time-step, the resulting LT value is greater than 1. This effect is particularly evident for days with a clear sky or intermediate sky. In the presence of a prevalently cloudy sky (see as an example the case of November 3, 2015 in fig. 4), the LT remains close to the unity.

Considering the impossibility of taking such a highly dynamic behavior of the LT throughout a single day and a full year, the median value of the LT calculated from the illuminance profiles recorded was assumed as an annual constant value. This value was found to be LT = 0.76. As a result, a glazing with a LT of 0.72 coupled with algae system with a LT of 0.76 was used for Daysim simulations to calculate the amount of daylight within the considered space and the corresponding energy demand for lighting. The package glazing+algae was therefore modeled in Daysim using a glazing with an equivalent LT of 0.55 (resulting from 0.72x0.76).

glass without PBSs   glass with PBSs

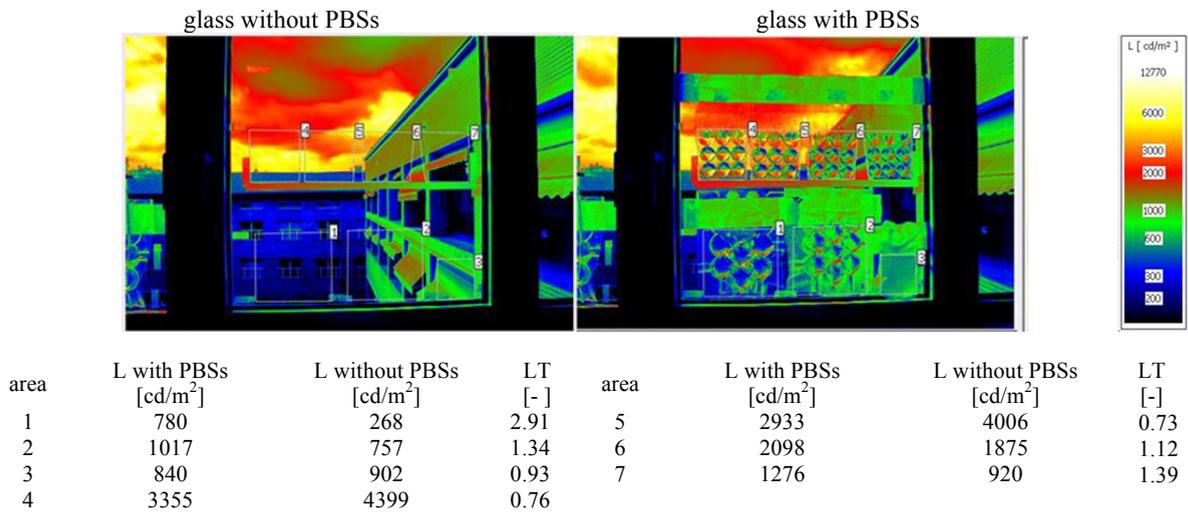| area	L with PBSs [cd/m^2]	L without PBSs [cd/m^2]	LT [-]	area	L with PBSs [cd/m^2]	L without PBSs [cd/m^2]	LT [-]
1	780	268	2.91	5	2933	4006	0.73
2	1017	757	1.34	6	2098	1875	1.12
3	840	902	0.93	7	1276	920	1.39
4	3355	4399	0.76				

Fig. 3. Example of luminance maps recorded for one day and of the corresponding LT calculated.
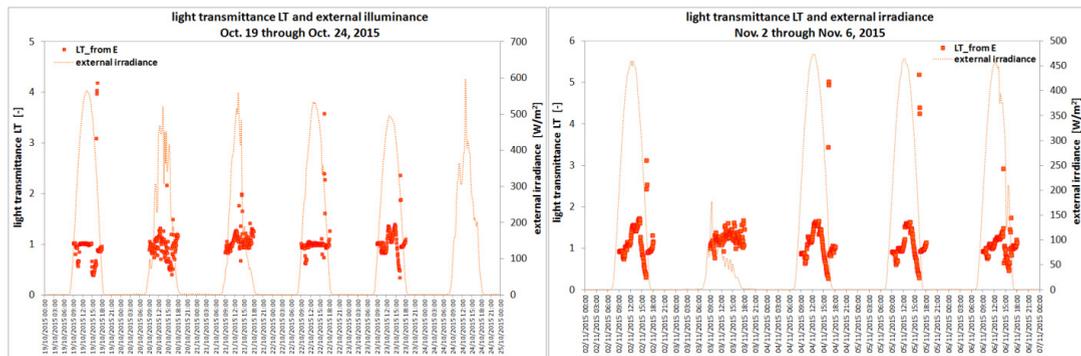

Fig. 4. Example of illuminance data recorded for two weeks and of the corresponding LT calculated. External irradiance are also plotted to allow sky conditions to be identified (clear vs. overcast).

3.3. IEQ (visual comfort) and energy saving simulations

A number of metrics was calculated through Daysim and Radiance simulations: DF, CBDM, DGP and ED_l. The results which were found are visualized in Figures 5-7: per each metric, the values for the package glazing+algae-system (labeled 'algae 55') are plotted versus the corresponding values for the package glazing+venetian blind (labeled '74+blinds'). In more detail, fig. 5 shows the DF and the CBDM annual values, fig. 6 the annual DGP values and fig. 7 the annual ED_l values: in these figures, the activation profiles of the venetian blinds for both controls (based on the irradiance set-point and on the DGP set-point) are also plotted. DGP values are grouped in the following ranges, according to what classified by Wienold et al. [13]: *i*) DGP > 0.45, 'intolerable' glare; *ii*) 0.40 < DGP < 0.45, 'disturbing' glare; *iii*) 0.35 < DGP < 0.40, 'perceptible' glare; *iv*) DGP < 0.35, 'imperceptible' glare.

In short, the following main considerations can be drawn:

- DF: DF_m values are over 3% for both glazing types (algae55 and 74+blind). In the presence of the system glazing+venetian blinds, DF_m values are higher than in the presence of the algae-system (+27%). This is due the fact that the DF_m refers to an overcast sky, under which the venetian blind is not used. In this condition, the traditional blinds admits more skylight into the room according to its higher LT value
- $sDA_{300/50\%}$: an increment was observed for all cases with the algae-system (range: +22.0%-165.7%)
- DGP: a higher occurrence of glaring condition throughout a year was observed in the presence of the package 'Algae 55'. In Turin, the 'intolerable glare' (DGP > 0.45) occurs for 19.0% of the annual occupancy time for the

algae system, compared to an occurrence of 11.3% and of 8.8% for the blinds (controlled based on the irradiance set-point and on the DGP set-point, respectively). Conversely, the occurrence of 'imperceptible' and 'perceptible' glare conditions (DGP < 0.40) is in favor of the system with blinds: 82.4% and 81.3% for the two controls vs. 75.3% for the system 'algae 55'. These results refer to the site of Turin and are displayed in detail in fig. 6 (similar results were found for the case of Palermo)

- ED_l: with respect to the case with traditional glazing+venetian blinds, ED_l values in the presence of the algae-systems decrease for all the considered cases (with the exception of south-facing rooms in Palermo): this decrease was in the range -3.3% to -57.0% for a target illuminance of 300 lx and +3.3 to -48.0% for Palermo.
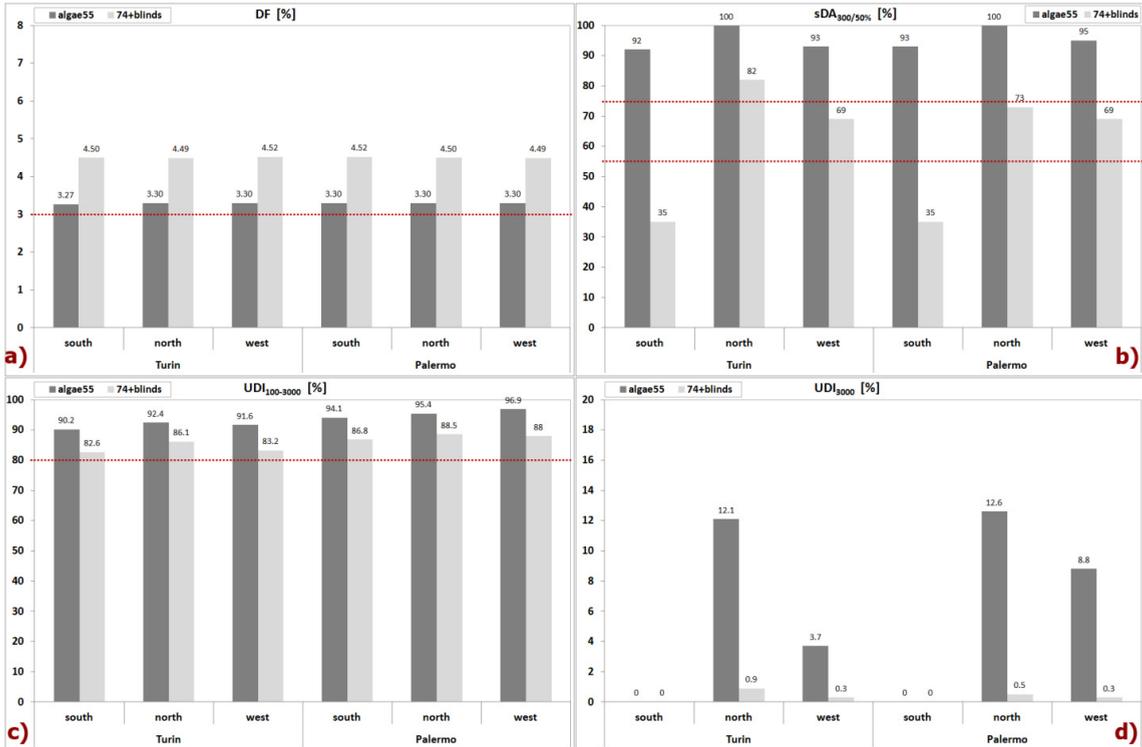

Fig. 5. Comparison of the daylight amount in the same room equipped with the algae-system and with a traditional venetian blind: results in terms of DF (a), $sDA_{300/50\%}$ (b), $UDI_{100-3000}$ (c), UDI_{3000} (d).
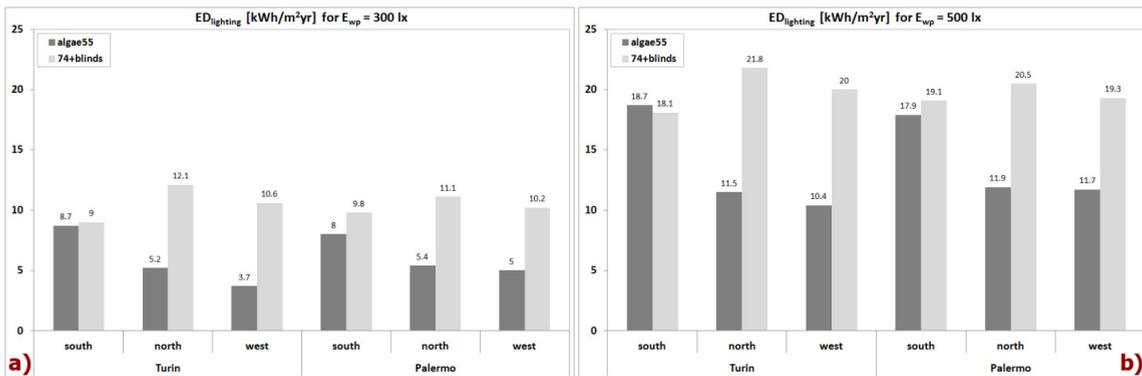

Fig. 7. Comparison of the daylight amount in the same room equipped with the algae-system and with a traditional venetian blind: results in terms of energy demand for lighting ED_l for a work plane illuminance of 300 lx (a) and of 500 lx (b).
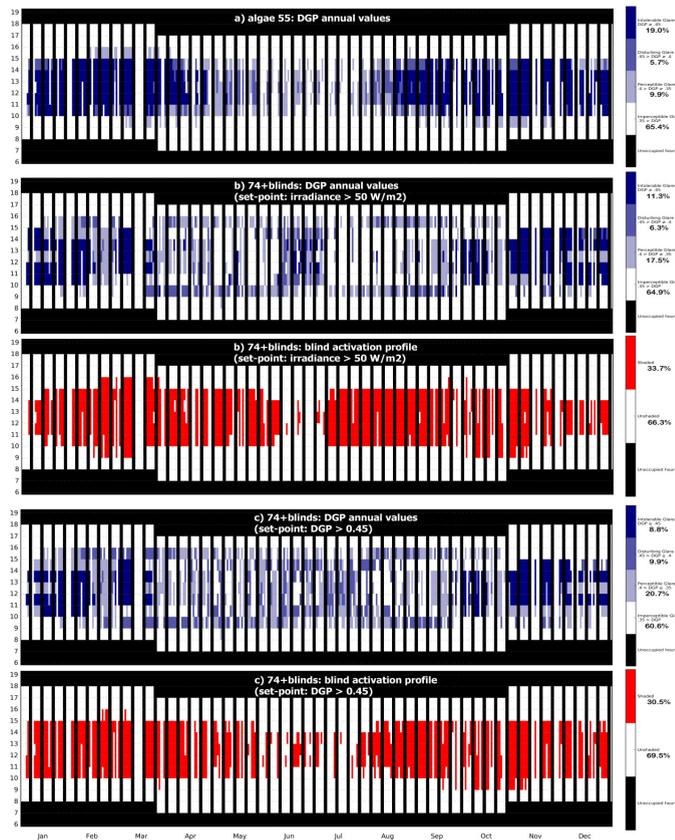
Fig. 6. Annual DGP values in the same room equipped with the algae-system and with a traditional venetian blind. Results for Turin.

4. Discussion and future work

The originality of this study was to have prototyped innovative packages where algae were used as static screens (PBSs), and to have measured the photometric performances of these systems, in terms of light transmittance, visual comfort (CBDM), and energy demand for lighting. From an operational viewpoint, it is worth noticing that both the alage-systems and the venetial blinds limit the view to the outside for the occupants: this is constant with the algae-system throughout a year, when the algae are applied to the whole window (as assumed in the study), while it occurs with a frequency in the presence of the blinds (pulled down less frequently when the blind control through the DGP set-point is used - 30.7% versus 33.5%). To maintain the possibility of a view out, the best solution might be to subdivide the window in two horizontal stripes, applying the algae system to the upper stripe (the 'shading window') and leaving a double pane glazing without blinds for the lower stripe (the 'view window'). This solution will be implemented and monitored in a real room as a future step of the still on-going research. Furthermore, in order to increase the micro-algal growth rate, further study is being made to investigate PBS prototypes, with lower cubicles thickness, different cubicle packaging and shape, and fluid recirculation inside PBSs. An optimization of the glazing layout becomes a crucial factor to effectively match view out and shading purposes.

5. Conclusions

Disposable plastic bags with circular cubicles were used as photo-bioreactors for microalgae cultivation to obtain static screens for windows. Prototypes with different layout, size, shape and surface, area/volume ratio of the cubicles, as well as for the presence/absence of mixing by bubbling air, were compared. The square packing of

cubicles performed better than the hexagonal ones and mixing operated by air bubbling was not necessary. More precisely, SCC with organic (PP-M) and inorganic carbon source (NaB-M50) showed μ_{max} values of 0.009 and 0.006 h^{-1}, respectively. Moreover, NaB-M50 medium, based on an inorganic carbon source, is cheaper than PP-M (organic C-source) and allows *S. obliquus* to be cultivated in the static screens.

From the daylighting exploitation viewpoint, the LT of the algae system was observed to be changing with time, with values over 1, due to the scattering effect produced by both the algae and the cublicles, which act as lenses. All daylight metrics reveal that the daylight amount in a room in the presence of the algae-system was higher compared to a glazing with venetian blinds. As a result, the energy demand for lighting ED$_l$ decreased (up to -57%). On the other hand, this higher daylight amount also results in more frequent visual discomfort for the occupants, as shown by the annual DGP values. It is interesting to observe the difference of DGP for the two algorithms to control the blinds: better results were found when a DGP based control was used (which is a visual comfort criterion), compared to the case of irradiance based control (which is a thermal comfort criterion).

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