Environmental Engineering Research

Environ. Eng. Res. 2021

Research Article

https://doi.org/10.4491/eer.2020.122

pISSN 1226-1025 eISSN 2005-968X

In Press, Uncorrected Proof

Use of double-glazed window as a photobioreactor for CO_2 removal from air

Hamidreza Rezazadeh[1], Maria Kordjamshidi[2], Ferial Ahmadi[2†], Alireza Eskandarinejad[3]

[1]*Faculty of Architecture and Urbanism, Art University of Isfahan, Isfahan, Iran*
[2]*Faculty of Art and Architecture, University of Mazandaran, Babolsar, Iran*
[3]*Department of Civil Engineering, Faculty of Engineering, Golestan University, Gorgan, Iran*

Abstract

The important issue of increasing CO_2 emissions to the atmosphere requires developing the environmentally sustainable strategies. One of the most innovative approaches in building design is using the microalgae photobioreactor (PBR) façades. In the current research, performance of a new green window was examined as an environmentally friendly method for the noted purpose. This window is a double-glazed window wherein the space enclosed by its two glasses was used as a PBR system. This window was investigated in two different conditions, namely as a window installed in a wall opening as a building façade element and also in laboratory condition. The experiments of the former condition were performed in Tehran city, where is known for the greatest air-polluted city in Iran, while tests of the later were carried out in Bablosar city located in northern Iran. Experiments include measuring absorption amounts of CO_2, temperature, optical density of cultivation medium, and evaporation. The obtained results validate performance of the proposed green window in decreasing CO_2 amounts. It was also observed that microalgae growth decreased the window transparency so that, in observing the general rules of Islamic and Iranian architecture, can enhance the visual privacy from non-mahram adjacent neighbors for Muslim women.

Keywords: CO_2 removal, Double-glazed window, Environmentally sustainable façade element, Microalgae, Photobioreactor, Window transparency

Received March 12, 2020 **Accepted** April 21, 2020

† Corresponding Author
E-mail: f.ahmadi@umz.ac.ir
Tel: +98-11-35302750
ORCID: 0000-0001-5901-6072

1. Introduction

During the last decades, cities have been rapidly developed due to various reasons such as the world population growth. The Department of Economics and Social Affairs of United Nation, Population Division illustrated that the world population will increase to 9.7 billion and 11.2 billion people in 2050 and 2100, respectively [1]. In addition, UN estimated that 70% of world population would reside in urban region in 2050 [2]. Such growth of urban residencies along with a dramatic rise in non-renewable energy (e.g. energy provided by fossil fuels) consumption can effectively increase CO_2 emissions to the atmosphere [3]. Moreover, there are the other forms of not-depleting resources that can be regularly replenished. The produced energy using such resources is termed as the renewable energy (e.g. electricity generated by wind, hydropower, and solar resources). The technologies of renewable energy can emit the greenhouse gases (GHGs) in different way compared to the fossil fuel burning plant [4]. As noted by Kumar et al. [4], the GHG emissions would also have adverse effects on the climate change and subsequently on agriculture, environment, etc. As stated in the report of Intergovernmental Panel on Climate Change (IPCC), 76% of anthropogenic GHGs came from carbon dioxide (CO_2) in 2010 [5] which would be double in 2035 [6]. Therefore, the reduction of CO_2 could play an important role in rectifying the global warming issue [7-11]. Other examples of GHGs include methane (CH_4) and nitrous oxide (N_2O) (see [12] for more details).

Through reviewing recent studies, it can be found that there are several techniques in CO_2 sequestration such as biological-, physical-, and chemical-based methods [6, 8, 13, 14]. The various processes such as reducing CO_2 emission sources along with removing the noted gas from the atmosphere is termed as “carbon sequestration” [9]. Among those techniques,

Biological-based methods are more appropriate for environment [15, 16]. Moreover, the biological method of CO_2 sequestration is as much low-costliness as the other two noted methods [14, 17]. As an example for the biological CO_2 reduction, terrestrial plants and photosynthetic microorganism through photosynthesis process absorb carbon dioxide. The terrestrial plants can decrease 3-6% of CO_2 emissions [17], while the efficiency of CO_2 mitigation provided by the photosynthetic microorganism such as microalgae and cyanobacteria is from 10 to 50 times better than those plants [18-20]. In addition, it should be mentioned that these organisms could grow several times faster than the terrestrial plants [21, 22]. Generally, there are many research programs that address using microalgae in mitigating GHG emissions such as the financial support for the treatment of wastewater, reducing CO_2 emissions from coal power plants, and mitigation of GHG emissions by US Department of Energy (DOE), the office of fuels development at DOE, and Japanese R&D, respectively [15]. It should be noted that the net CO_2 in the atmosphere would not increase because produced CO_2 from burning cancels out CO_2 absorbed by plants during photosynthesis [23]. Thus it would lead to mitigation of global warming potential (GWP).

Building façades plays a crucial role in reducing energy consumption and environmental impacts of using the non-renewable energies [24]. The high non-renewable energy consumption creates urban heat island and increases CO_2 emissions in the atmosphere. Thus, the development of the environmentally sustainable façade systems [25] has nowadays become an important issue in the design process. Wong et al. [26] stated that one of the sustainable strategies is using the vertical greenery systems that could significantly mitigate urban heat islands through their photosynthetic process [27]. It would be helpful to mention that among the various vertical

greenery systems, the algae façade has been recently proposed as an appropriate replacement of glazing systems [28]. Furthermore, the integration of microalgae into the building façade can improve air quality, provide good daylight access, and create healthy and livable buildings [27, 29].

The cooperation of Arup and the German consultancy SSC (Strategic Science Consult) results in constructing the first Bio-Intelligent Quotient (BIQ) building in Hamburg, Germany [27]. This BIQ building uses a specific type of vertical greenery systems in which the algae cultivation acts as a mechanism of self-production of electricity. A microalgae photobioreactor (PBR) façade is used in this project in order to generating the renewable energy. This façade is composed of the microalgae PBR panels that can convert the light into heat and biomass through the thermal and the photosynthetic processes, respectively. The general mechanism of PBR panel constructed in the present research is akin to the corresponding one developed by the Arup. Nevertheless, there are several differences in these two PBR panel types. Comprehensive comparisons of those panels can be found in researches carried out by Sardá and Vicente [30], Öncel et al. [31], and Elrayies [27]. This research investigates constructing a new PBR-type panel in which an indigenous microalga is employed to carry out the photosynthetic process. Literature reveals that little work has been made yet to propose using a PBR system in the space enclosed by two glasses of a double-glazed window. Moreover, it should be remarked that the photosynthetic process results in the CO_2 decrease that can ameliorate harmful environmental impacts of the CO_2 emission. Along with the noted application, it is worth mentioning that, with regard to vernacular architecture, such a panel could be used to increase confidentiality of Iranian houses in polluted urban areas.

2. Material and Methods

2.1. Panel Selection

Several factors should be considered in selecting a proper panel for the cultivation of microalgae: 1) available system types of microalgae cultivation; and 2) the main purpose of the selected panel, which might be employed as a building façade or a double-glazed window. Generally, there are two main types of cultivation system such as open-air ponds and closed PBRs (see [27, 31, 32] for more details). The latter type is of interest herein because such a system could be employed in the building façades and the double glazed windows, which is the ultimate aim of this research. It can be noted that the first two factors mentioned above closely rely upon each other. The attempt made in this study is to fabricate a new regional compatible PBR-type panel that suits Iran cities. The regional compatibility of those panels could be achieved by employing a standard window dimensions industrially produced in Iran, along with using a native microalga in order to facilitate preparing the required cultivation inputs.

The PBR panel examined in the present work is akin to the double glazed window, whereas in the PBR panel, the enclosed space between two glasses is filled with cultivation of microalgae instead of Aragon gas. The standard width and height of a residential building window are ranged from 40 to 90 cm, and from 100 to 180 cm, respectively [33]. The minimum sizes (i.e. 40 cm × 100 cm) of a window are selected for saving in effort and expense of the experiments. Moreover, based on the recommendation provided by Hormozgan Construction Engineering Organization [33], the standard thickness of the space enclosed by two glasses could be considered as 8, 12, 16, 20, and 24 mm in the double glazed window. In this regard, Degen et

al. [34] depicted that the PBR panel with thickness of 15 mm would be more productive rather than the other thickness values. Therefore, by comparing those values recommended by Hormozgan Construction Engineering Organization [33] and Degen et al. [34], the culture layer thickness of 16 mm is selected. It is worthy of notice that, by applying such a thickness value in producing the PBR panel, the light zone would be proportional to dark zone. In addition, in designing the PBR panel, the surface area to volume ratio is a paramount parameter because it can optimize the performance of panel by increasing the panel area exposed to light as well as reducing the travel distance of light through the panel [35-37]. In the other words, absorption of light has a considerable effect over an efficacy of the PBR panel performance.

2.2. Microalgae Selection and Cultivation

There is a variety of microalgaes which can be used to sequester the CO_2 [38, 39]. Various factors can effectively contribute to better selection of the proper microalgae for the purpose of the current study. The primary question should be addressed here is that, to account for an economical manufacturing the proposed PBR panel, how the general production expenses could be considerably decreased. These expenses consist of costs that should be paid for preparing the panel structure, sufficient provision of the microalge, and nutrients required for feeding the microlage. Due to using the standard panel as a double-glazed window, the first mentioned expenditure may be unalterable. Moreover, the last one (i.e. the nutrients) depends on the type of microalgae would be selected for cultivation. Hence, the type of microalgae should be carefully selected to afford the optimized PBR panel. Consequently, an economical production of the PBR panel would rely on the accessibility and productivity of the microalgae as well as its cost. To

obtain the aforementioned objective and fulfill indigenous conditions of the studied region for microalgae cultivation, *Chlorella Vulgaris* species is selected. It should be noted that this species could meet the requirements for growth in the seawater of Caspian Sea by applying some treatments [40]. Furthermore, the Caspian Sea is not far away from the area of interest. For the sake of convenience and reduction in expenses, the mentioned species is provided by the Algae Biotechnology Center of Persian Gulf, Bushehr, Iran.

As noted earlier, light absorption is a vital parameter in microalgae cultivation. Hence, a crucial need for preparing an optimized condition for light absorption should be fully met. In this regard, the intensity of light over the cultivation medium should be controlled because if this intensity increases, large amounts of microalgae cells will be died, on the contrary, a serious shortage of light could be led to decrease of microalgae photosynthesis and CO_2 absorption as well as productivity of the PBR panel [41, 42].

An aqueous solution with 25 ppt salinity is developed by combining the urban water and the sea-salt. This solution was also used by Emad abadi et al. [43] to cultivate the *Chlorella Vulgaris*. A working volume of the PBR panel culture medium is five liters. Under sterilized conditions, the working culture medium is prepared by mixing the abovementioned aqueous solution of 4 L and 1 L the stoke solution of *Chlorella Vulgaris*.

The PBR panel is set up as a window of a building located at a highly air-polluted region of Tehran (i.e. capital of Iran). A schematic representation of the PBR panel used as the double-glazed window is shown in Fig. 1. In addition to those details are drawn in Fig. 1, an air compressor is employed to pump the polluted air uniformly from outdoor environment into the culture site by using an air controller valve and an electronic flowmeter. The pumped air is fed

by a bubble blower embedded at the bottom of window. Those bubbles ascend thorough the cultivation media and then the process of photosynthesis is conducted by the *Chlorella Vulgaris*. During this process, CO_2 is absorbed and oxygen is produced by the noted microalgae. A void space of 30 cm height above the surface level of microalgae cultivation solution is considered to maintain the produced oxygen gas, which is collected by a gas oxygen sucker and then is released into the air. Moreover, there is a possibility of entering a fraction of this oxygen gas into the photobioreactor using a setting device. Therefore, the dissolved oxygen in the cultivation media is collected by the soluble oxygen sucker. Additionally, the release process of the dissolved oxygen is identical to the corresponding process mentioned above for the oxygen gas.

The users of the PBR panel should deal with the issue of sedimentation of biomass in the course of cultivation process. Here, an air injection mechanism from the bottom of PBR panel is employed to produce bubbles, which cause floatation of the microalgae and, in turn, preventing from sedimentation of biomass.

2.3. Experiments

The present section is devoted to the performed tests and their results. The proposed green window was evaluated in two different sites and conditions. The most important difference of those conditions regards how the PBR panel was installed and located. The first set of tests was carried out on a the PBR panel installed as a double glazed window located in a wall opening, whereas in the second one, the noted PBR panel was examined in a laboratory condition in which the panel was placed on the floor because the required wall opening was not available. Moreover, it should be mentioned that the first site was located in Tehran city, while the

laboratory implemented as a new site for conducting the second set of tests, was located in Babolsar city. Moreover, there are two main causes for testing at the second site (i.e. the laboratory in Babolsar city) where the current research was followed up: 1) limitation of time and place, to accomplish the objectives of the tests in a certain period of time; 2) limitation in accessing an apparatus to measure the intensity of light passing through the studied panel. However, in comparison with the second site, it must be acknowledged that the first place of tests was in further agreement with the practical situations. In the following subsections, first the results of the tests performed in Tehran will be addressed and then laboratory measurements of Babolsar city will be presented.

2.3.1. Tehran tests

At the first step, the cultivation room and the PBR panel were illuminated using a fluorescent lamp to maintain the light intensity at 1,000 lux associated with the light-dark cycle of 12:12 hours. The lighting by the fluorescent lamp was carried out from 10 pm to 10 am (lighting period). On the contrary, the dark period was considered as the time interval from 10 am to 10 pm. Temperature of experiment room was varied between 25 and 27℃. For aerating the culture medium, an aquarium pump was used for continuous outdoor air supply along with the circulation of nutrients and microalgae. Additionally, as noted earlier, such a circulation resulted in avoiding the sedimentation of microalgae biomass. To attain main goal of this study (determining whether or not the proposed PBR panel would absorb CO_2 of the polluted air of study area), the air of one of the most heavily polluted metropolitan area in Iran, viz., Tehran city

was selected as a case study. The studied region of the present investigation was located at Valiasr Square, close to the air quality monitoring station of Fatemi Street.

CO_2 amounts were measured by a CO_2 analyzer (i.e. KIMO AQ110 Carbon Dioxide Meter) during the traffic rush hours of the abovementioned area. The number of algal cells was measured three times per day during reproduction days. Particular attention was paid to select an optimum number of measurements per day in order to consider the highest CO_2 concentrations existing at the most polluted times of day. Therefore, during each experiment day, data was gathered at three points of time including 10 am, 1 pm, and 4 pm.

2.3.2. Babolsar tests

In the second set of experiments that conducted in Babolsar city and as the supplementary tests, the CO_2 absorption and the intensity of light passing through the panel were measured each 12 hours for nine days. In other words, those parameters were examined and recorded eighteen times. In a similar manner to measuring in Tehran city, the illumination was provided by the 1,000 lux fluorescent lamp with the same fixed light-dark cycle for the green window. The outdoor air was continuously supplied by the aquarium pump for the system. In contrast to the natural polluted outdoor air provided for cultivating the microalgae in the site located in Tehran city, in Babolsar city, the aquarium pump was placed close to a chimney which was permanently active during the entire functioning period of the green window system. Furthermore, in the case of Babolsar city, the other required processes such as aeration and circulation were done the same as the corresponding ones for the previous site.

The first data of the 4.5 L aqueous solution in the absence of the 0.5 L stoke solution of *Chlorella Vulgaris* was recorded. Therefore, contrary to the previous case (Tehran city), the new mixture ratio of 9:1 v/v was used to prepare a cultivation medium of the aqueous and the stoke solution of *Chlorella Vulgaris* for the tests of Babolsar site.

3. Results and Discussion

3.1. CO_2 Removal at the Tehran Site

Table 1 shows the data measured regarding the input, output and absorption amounts of CO_2 during the six days according to the proposed methodology. Furthermore, at the same time, temperature of input air to the cultivation medium along with evaporation from the aqueous solution are reported in Table 1. Such additional records were used to describe in more detail the conditions under how cultivation was performed during all the time of test.

The first measurements of those noted parameters (i.e. at 10 am of first experiment day) were conducted using the aqueous solution (which had volume of 4 L) in the absence of the stoke solution (which had volume of about 1 L) of *Chlorella Vulgaris*. The mentioned measurement led to obtaining the input and output CO_2 amounts of 1091 and 962 ppm, respectively (Table 1). This means that the PBR panel absorbed 11.8 percent of the CO_2 without adding any stoke solution of *Chlorella Vulgaris* to culture medium. In the following stage, 1 L stoke solution of *Chlorella Vulgaris* was immediately added to the aqueous solution (this means that mixture of the aqueous solution and the stoke one in 4:1 (v/v) ratio) and three hours thereafter (i.e. at 1 pm of first experiment day) the measurements of interest were conducted. In this stage, the CO_2 absorption decreased from 11.8 to 6.1 percent. Perhaps such a reduction

would be due to shocking of microalgae arising from their settling down to the new conditions. The data shows that absorption of CO_2 was insignificantly increased to 7.1 percent at 4 pm of first day of experiment.

In the second day of experiment, the CO_2 absorption percentage was notably increased to 24.5 at 10 am. This may be due to matching up the microalgae and their culture medium along with improving efficiency of the system over the time. Table 1 indicates that at the third day, at 1 and 4 pm, the green window absorbed a greater relative amount of CO_2 than its preceding two days. Thus, it could be concluded that the microalgae grew progressively. At the next day of test (i.e. fourth day), relatively similar amounts of CO_2 absorption were obtained for measuring at 10 am and 1 pm, compared to the results of the third day. However, at the 4 pm of fourth day, the CO_2 amount absorbed by the green window (6.5 % absorption) was lower than the corresponding value for third day (CO_2 absorption of 13.8 %). A noteworthy increase of the CO_2 absorption over the last two days of experiment (i.e. the fifth and sixth days) demonstrates a considerable improvement in the efficiency of the green window.

By comparing the amounts of CO_2 which were absorbed by the green window at 4 pm (in the middle of dark period) in each day with the corresponding value for 10 am (end of lighting period), it could be noted that, in the presence of light of the fluorescent lamp, the microalgae contribute more in absorption of CO_2 during the photosynthesis. Such an issue was due to the respiration of the microalgae during the dark period and also evapotranspiration. However, because of using the closed PBR here, the latter could be considered as of no importance. In addition, it can be clearly observed from Fig. 2 that the average percentage of CO_2 absorption per

day generally increased from 6.6 to 45.4 % in the course of experiment. Nevertheless, the aforementioned figure depicts that this parameter interestingly decreased at the fourth day of test.

3.2. Applications of Transparency Reduction of the Proposed Green Window

As depicted in Fig. 3, the growth of microalgae results in lowering the transparency of the green window as well as its color over the time. Such a color variation can demonstrate a wide range of color spectrum due to growing of microalgae and increasing its cell density. This issue can be employed to achieve three different applications by using either the green window proposed here or other forms of PBR. These applications include: 1) From the perspective of urban landscape design, the building façades can be designed by organizing the green windows having the different elapsed times from the start of cultivation process in order to construct a color spectrum towards different directions (see Fig. 4) as well as having a dynamic color over the time (regarding Fig. 4, it should be noted that the changes in color of the windows are predicted using the fitted polynomial equation which will be presented in Fig. 6. This is done based on the assumption that there is a relationship between color spectrum and optical density of cultivation medium); 2) Utilizing the green window as an apparatus for producing shade in regions with hot and dry climate (such a shade could decrease the indoor temperature of building); 3) Decrease of the window transparency can lead to limiting the visibility (this issue is compatible with the Iranian culture regarding staying concealed the inhabitants' privacy from non-mahram men). Moreover, it is worthy to emphasize that there are other applications of PBRs such as an open microalgae PBR as an urban fountain, biofilters over the buildings in improving the air quality, bioinsulator in decreasing the noise, artificial trees in urban spaces, closed circle PBRs for

parking canopies, curtain-wall PBRs, and algae biofaçades [31]. Fig. 5 illustrates a microalgae biofaçade that is designed based upon the color spectrum of indoor light which is produced by the stained window in the Iranian houses.

3.3. CO_2 Removal at the Babolsar Site

As can be seen in Table 2, the input CO_2 of this stage of experiment was observed as 611 ppm where 11 ppm was absorbed solely by the initial aqueous solution. Moreover, the light intensity passed from the green window was measured as 950 lux. This value demonstrates that the initial aqueous solution could decrease light intensity of 50 lux due to its opacity. In the next step, after adding the 0.5 L stoke solution of *Chlorella Vulgaris* at the start point of light period, data shows that the culture medium produced CO_2 by 31.1% (i.e. 190 ppm). As earlier described, settling down of microalgae to a new condition would led to their shocking.

Hereafter, the data were recorded every 12 h at the end of light and dark periods. After 12 h (i.e. end point of light period for first day), 27 ppm CO_2 was absorbed by the culture medium (Table 2). Moreover, the temperatures of input and output air were 23.8 and 24.4℃, respectively. This increase of 0.6℃ in temperature demonstrates that the photosynthesis of microalgae is an exothermic process. Such an issue would be carefully considered in providing the thermal comfort of buildings. In comparison with data of the prior stage, second measurements recorded at 24 h after adding the stoke solution (end of dark period) indicate that the CO_2 absorption has been approximately doubled (63 ppm). The trend of measurements observed in the present work is in good agreement with the described general phases of algae growth in the literature. (see [44] for more details).

3.4. Optical Density Variation

To assay the growth rate of the *Chlorella Vulgaris* species, the turbidity technique has been utilized in the Babolsar site. In order to find the proper time of balanced cell growth by this method, the standard curve in seven dilutions of main stock (i.e. 1:1, 1:2, 1:5, 1:10, 1:20, 1:50, 1:100 stock solutions) was developed. This curve was calculated based on the optical density in order to gain the cell numbers of each reading. As it is prevalent in the turbidity technique, an optical density of the microalgae cultivation medium was measured by a spectrophotometer. All of the readings were carefully performed on the proper λ_{max} which was calculated as a suitable wavelength for reading to get an approximate cell numbers. In accordance with the results of this test, the optical density of 0.033 for the wavelength of 540 nm was obtained.

Fig. 6 provides information on the variation of the optical density as a function of cultivation time. In this figure, it can be seen that, the optical density increases slightly until the cultivation time of 72 h. It then rises dramatically by almost 150% from the time of 72 h to about 192 h; thereafter, it declined suddenly by less than 10% until the end of experiment. Hence such a variation indicates the dynamic characteristic of visual transmittance of the green window over the time. Moreover, equation of the fourth-order polynomial curve fitted to the data points is shown in Fig. 6. This equation depicts the optical density variation as a function of cultivation time for results of tests carried out in the laboratory located in Babolsar.

According to the results reported here, this technique may be a proper method to measure the amount of transmitted light through the proposed green double-glazed window. It is worth, however, that the aforementioned amount can be varied through the entire life cycles of

microalgae (i.e. the growth of microalgae) in the cultivation medium because these cells can cause absorption and scatter of light. Such a feature in glazing systems can be employed to control the visual transmittance of those systems under the different seasonal conditions. Furthermore, the color of glazing can play an important role in the satisfaction of occupants in buildings with various functions such as residential, official, commercial, and educational buildings, and those for religious purposes. With regards to the capability of the proposed green window in changing both the visual transmittance and color of glazing systems, it should be noted that these characteristics could significantly affect several issues such as working performance, mood, alertness and sleepiness, and visual satisfaction for the occupants [45]. Umdu et al. [46] investigated the ability of the façade-integrated PBRs to act as an effective insulation system. Therefore, the noted green window could also be utilized to improve thermal performance of buildings.

4. Conclusions

In order to the development of the environmentally sustainable strategies in mitigation of CO_2 emission, this study was carried out to examine the performance of using a new regional green window (which can be considered as PBR panel system) in building façades.

The results show that the designed PBR panel (green window) can significantly decrease CO_2 as expected. It is observed that CO_2 absorption generally tends to increase with microalgae growth over the time of experiments. Besides, the amount and intensity of solar radiation that reaches interior spaces of a building decreases with increasing the cell density of microalgae. This also results in decreasing indoor temperature of building. Therefore, the designed green

window can be introduced as a proper replacement for doubled glazed windows in hot and dry climate regions. Additionally, it was observed that increasing the cell density of microalgae decreases window transparency. Consequently, the reduction of transparency leads to limiting the visibility to great extent that enhances the visual privacy from non-mahram adjacent neighbors for female Muslim occupants. It is worthy to note that the Islamic designers must deal with the issue of visual privacy to observe the general rules of Islamic and Iranian architecture.

Acknowledgment

The authors would like to thank Tahereh Zahedi (Univeristy of Mazandaran) for helpful comments on this manuscript. The authors are also grateful to Professor Abasalt Hosseinzadeh Colagar (Univeristy of Mazandaran) for providing the laboratory facilities. We also are grateful for the constructive and critical comments of two anonymous reviewers.

Author Contributions

H.R. (Ph.D. student) conceived of the presented idea and carried out the experiments and wrote the initial version of the manuscript. M.K. (Assistant professor) and F.A. (Assistant professor) provided critical feedback and helped shape of the research, analysis and manuscript and supervised the findings of this work. A.E. (Assistant professor) encouraged H.R. to investigate the other aspects of the new green window regarding the window transparency and performed the computations and analyzed the data. All authors discussed the results and contributed to the final version of the manuscript.

References

1. United Nations, Department of Economic and Social Affairs, Population Division (2017). Probabilistic Population Projections based on the World Population Prospects: The 2017 Revision. Population Division, DESA. http://esa.un.org/unpd/wpp/.

2. United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, Online Edition.

3. Madlener R, Sunak Y. Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management?. *Sustain. Cities Society*. 2011;1(1):45-53.

4. Kumar A, Sharma MP, Yang T. Estimation of carbon stock for greenhouse gas emissions from hydropower reservoirs. *Stoch. Environ. Res. Risk Assess*. 2018;32(11):3183-3193.

5. Intergovernmental Panel on Climate Change (IPCC): Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

6. Milano J, Ong HC, Masjuki HH, at al. Microalgae biofuels as an alternative to fossil fuel for power generation. *Renew. Sustain. Energ. Rev.* 2016;58:180-197.

7. Radhi H. Evaluating the potential impact of global warming on the UAE residential buildings– A contribution to reduce the CO2 emissions. *Build. Environ*. 2009;44(12):2451-2462.

8. Zhou W, Wang J, Chen P, et al. Bio-mitigation of carbon dioxide using microalgal systems: advances and perspectives. *Renew. Sustain. Energ. Rev*. 2017;76:1163-1175.

9. Kumar A, Sharma MP. Estimation of soil organic carbon in the forest catchment of two hydroelectric reservoirs in Uttarakhand, India. *Hum. Ecol. Risk. Assess. Intern. J*. 2015;22(4):991-1001.

10. Kumar A, Sharma MP, Kumar A. Green house gas emissions from hydropower reservoirs: policy and challenges. *Int. J. Renew. Energ. Resour*. 2016;6(2):472-476.

11. Kumar A, Sharma MP. Estimation of greenhouse gas emissions from Koteshwar hydropower reservoir, India. *Environ. Monit. Assess*. 2017;189(5):240-251.

12. Kumar A, Yang T, Sharma MP. Greenhouse gas measurement from Chinese freshwater bodies: A review. *J. Clean Prod*. 2019;233:368-378.

13. Kim YS, Lee SH. Quantitative analysis of Spirulina platensis growth with CO_2 mixed aeration. *Environ. Eng. Res*. 2018;32(2):216-222.

14. Kumar K, Dasgupta CN, Nayak B, Lindblad P, Das D. Development of suitable photobioreactors for CO2 sequestration addressing global warming using green algae and cyanobacteria. *Bioresour. technol*. 2011;102(8):4945-4953.

15. Bhola V, Swalaha F, Kumar RR, Singh M, Bux F. Overview of the potential of microalgae for CO_2 sequestration. *Intern. J. Environ. Sci. Technol*. 2014;11(7):2103-2118.

16. Zhao B, Su Y, Zhang Y, Cui G. Carbon dioxide fixation and biomass production from combustion flue gas using energy microalgae. *Energy*. 2015;89:347-357.

17. Skjånes K, Lindblad P, Muller J. BioCO$_2$–A multidisciplinary, biological approach using solar energy to capture CO$_2$ while producing H2 and high value products. *Biomol. Eng.* 2007;24(4):405-413.

18. Wang B, Li Y, Wu N, Lan CQ. CO$_2$ bio-mitigation using microalgae. *Appl. Microb. Biotechnol*. 2008;79(5):707-718.

19. Ho SH, Chen CY, Lee DJ, Chang JS. Perspectives on microalgal CO$_2$-emission mitigation systems—a review. *Biotechnol. Adv.* 2011;29(2):189-198.

20. Langley NM, Harrison STL, Van Hille RP. A critical evaluation of CO$_2$ supplementation to algal systems by direct injection. *Biochem. Eng. J.* 2012;68:70-75.

21. Varma VS, Srinivasa SV, Suthanthararajan R, Ravindranath E. Algal Symbiosis in Reduction of Greenhouse gas (GHG) Emission and Bio-Energy Production. International Conference on Control of Industrial Gaseous Emission; 9 February 2012; Chidambara, India. p. 89-93.

22. Kargupta W, Ganesh A, Mukherji S. Estimation of carbon dioxide sequestration potential of microalgae grown in a batch photobioreactor. *Bioresour. Technol*. 2015;180:370-375.

23. Naik SN, Goud VV, Rout PK, Dalai AK. Production of first and second generation biofuels: A comprehensive review. *Renew. Sustain. Energ.Rev*. 2010;14:578-597.

24. Misawa Y, Hikone S, Nakamura M, Iwamoto S, Iwata M. Diagonally arranged louvers in integrated facade systems-effects on the interior lighting environment. *J. Facade Des. Eng*. 2014;2(3-4):163-182.

25. Kim KH. Beyond green: growing algae facade. ARCC Conference Repository: The Visibility of Research Sustainability: Visualization Sustainability and Performance; 27-30 March 2013; University of North Carolina, Charlotte, USA. p. 500-505.

26. Wong NH, Tan AYK, Chen Y, et al. Thermal evaluation of vertical greenery systems for building walls. *Build. Environ*. 2010;45(3):663-672.

27. Elrayies GM. Microalgae: prospects for greener future buildings. *Renew. Sustain. Energ. Rev.* 2018;81:1175-1191.

28. Kim KH. A feasibility study of an algae façade system. International Conference on Sustainable Building Asia SB13; 8-10 July 2013; Seoul, South Korea; p. 7-10.

29. Araji MT, Shahid I. Symbiosis optimization of building envelopes and micro-algae photobioreactors. *J. Build. Eng*. 2018;18:58-65.

30. Sardá RC, Vicente CA. (2016). Case studies on the architectural integration of photobioreactors in building facades. In: Pacheco Torgal F, Buratti C, Kalaiselvam S, Granqvist CG, Ivanov V, eds. Nano and Biotech Based Materials for Energy Building Efficiency. Springer, Cham; 2016. p. 457-484.

31. Öncel SŞ, Köse A, Öncel DŞ. Façade integrated photobioreactors for building energy efficiency. Start-Up Creation: The Smart Eco-Efficient Built Environment. In: 11 - Façade integrated photobioreactors for building energy efficiency. Woodhead Publishing; 2016. p. 237-299.

32. Baicha Z, Salar-García MJ, Ortiz-Martínez VM. et al. A critical review on microalgae as an alternative source for bioenergy production: A promising low cost substrate for microbial fuel cells. *Fuel Process. Technol*. 2016;154:104-116.

33. Hormozgan Construction Engineering Organization. Specifications and regulations for architectural design of residential buildings, Department of architecture, Publication of engineering organization, Bandarabbas; 2010 (in persian).

34. Degen J, Uebele A, Retze A, Schmid-Staiger U, Trösch W. A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect. *J. Biotechnol.* 2001;92(2):89-94.

35. Brennan L, Owende P. Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. *Renew. Sustain. Energ. Rev.* 2010;14(2):557-577.

36. Tamburic B, Zemichael FW, Crudge P, Maitland GC, Hellgardt K. Design of a novel flat-plate photobioreactor system for green algal hydrogen production. *Intern. J. Hydrog. Energ.* 2011;36(11):6578-6591.

37. Singh RN, Sharma S. Development of suitable photobioreactor for algae production–A review. *Renew. Sustain. Energ. Rev.* 2012;16(4):2347-2353.

38. Singh UB, Ahluwalia AS. Microalgae: a promising tool for carbon sequestration. Mitigation Adaptation Strategies for Global Change, 2013;18(1):73-95.

39. Cheah WY, Show PL, Chang JS, Ling TC, Juan JC. Biosequestration of atmospheric CO_2 and flue gas-containing CO_2 by microalgae. *Bioresour. Technol*. 2015;184:190-201.

40. Rezaei SS, Taghavi Jelodar H, Ganjian Khenari A. Studying the growth process of microalgae *Chlorella* using water enrichment of Caspian Sea in general medium. *J. Plant Res.* 2018;30(3):695-707.

41. Wang SK, Stiles AR, Guo C, Liu CZ. Microalgae cultivation in photobioreactors: An overview of light characteristics. *Eng. Life Sci*. 2014;14(6):550-559.

42. Perin G, Cimetta E, Monetti F, Morosinotto T, Bezzo F. Novel micro-photobioreactor design and monitoring method for assessing microalgae response to light intensity. *Algal Res*. 2016;19:69-76.

43. Emad Abadi M, Salarzadeh A, Foroughi Fard H. Effects of salinity and Gillard medium on the density and specific growth rate of *Chlorella Vulgaris*. *J. Aqua. Animals Fisher*. 2015;5(20):47-54.

44. Blair MF, Kokabian B, Gude VG. Light and growth medium effect on *Chlorella vulgaris* biomass production. *J. Environ. Chem. Eng*. 2014;2(1):665-674.

45. Chen X, Zhang X, Du J. Glazing type (colour and transmittance), daylighting, and human performances at a workspace: A full-scale experiment in Beijing. *Build. Environ*. 2019;153:168-185.

46. Umdu ES, Kahraman İ, Yildirim N, Bilir L. Optimization of microalgae panel bioreactor thermal transmission property for building façade applications. *Energ. Build*. 2018;175:113-120.

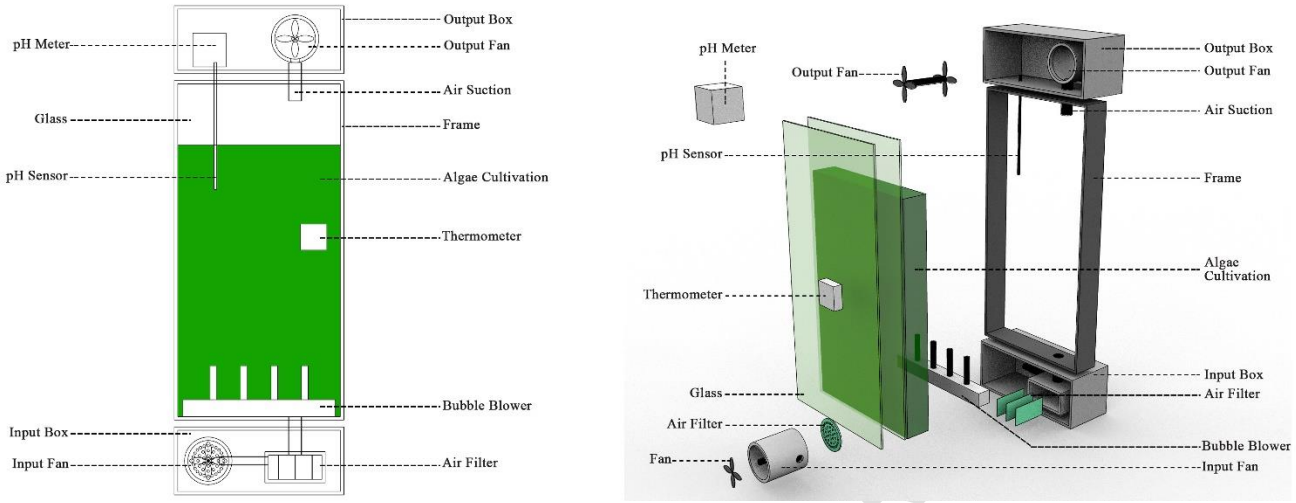

Fig. 1. Schematic illustration of the proposed green window along with its components. (a) Front view; (b) 3-D view.

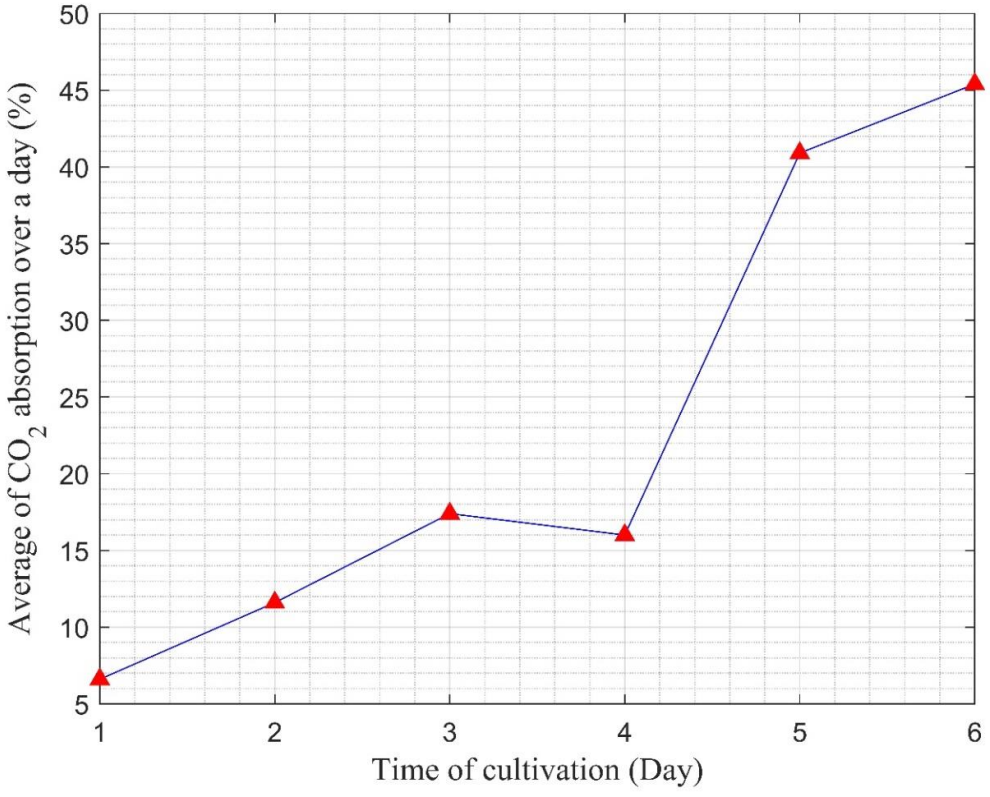

Fig. 2. Average percentage of CO_2 absorption by the green window per day.

Fig. 3. Variation of color and transparency of the green window. (a) Before microalgae culture; (b) After 12 h of microalgae culture; (c) After 180 h of microalgae culture.

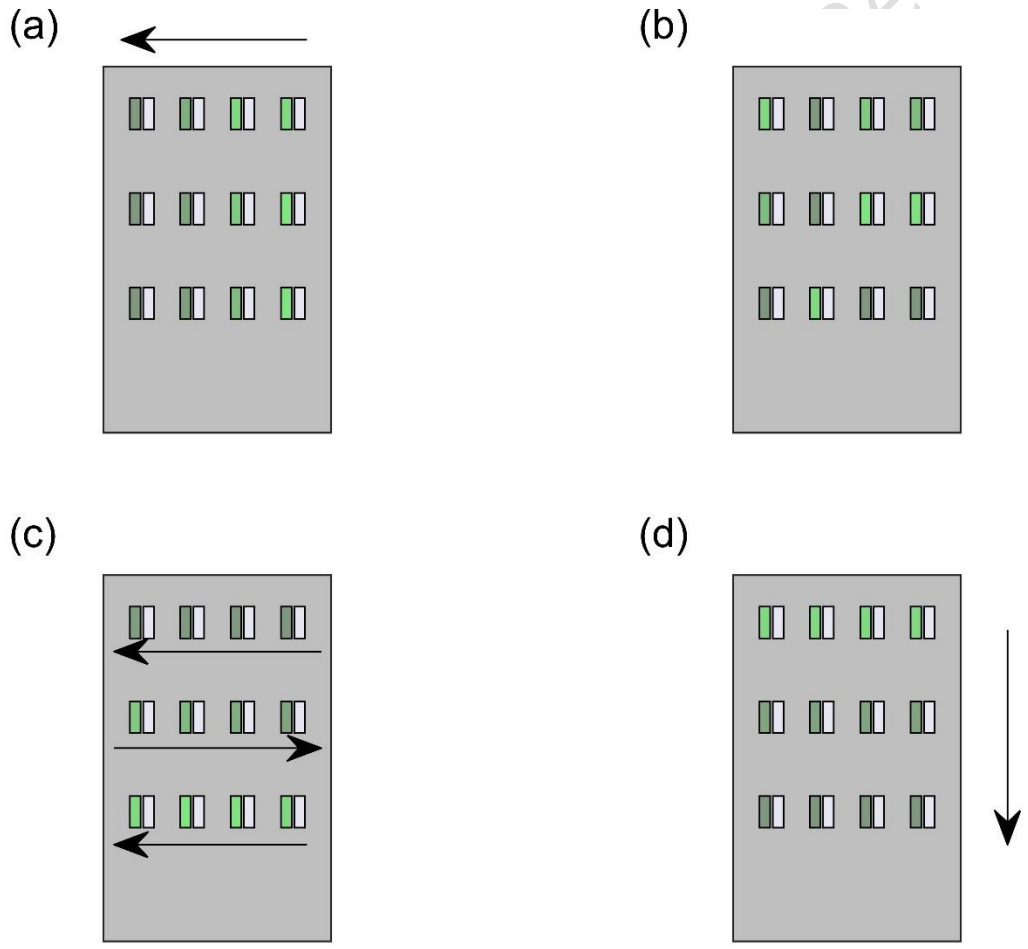

Fig. 4. Four hypothetical patterns of the green windows that are designed by the color spectrum feature of the microalgae cultivation medium. (a) Horizontal color spectrum; (b) Random color

spectrum; (c) Alternate pattern; (d) Vertical color spectrum. The directions of arrows show an increase of the elapsed time from the start of microalgae cultivation.

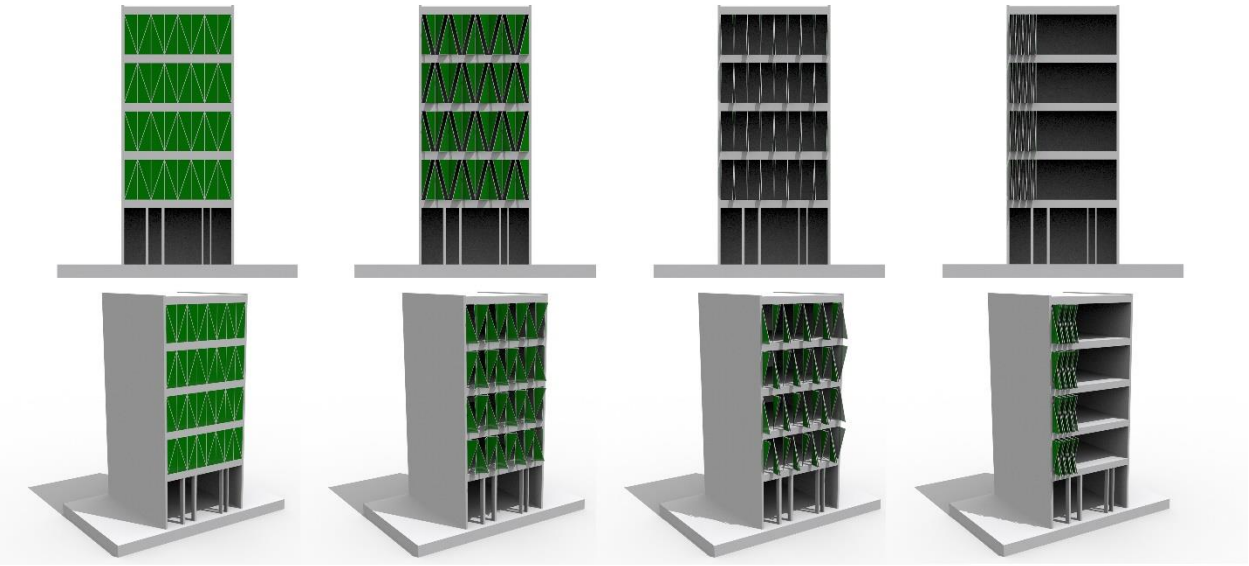

Fig. 5. Microalgae biofaçade inspired by Iranian houses.

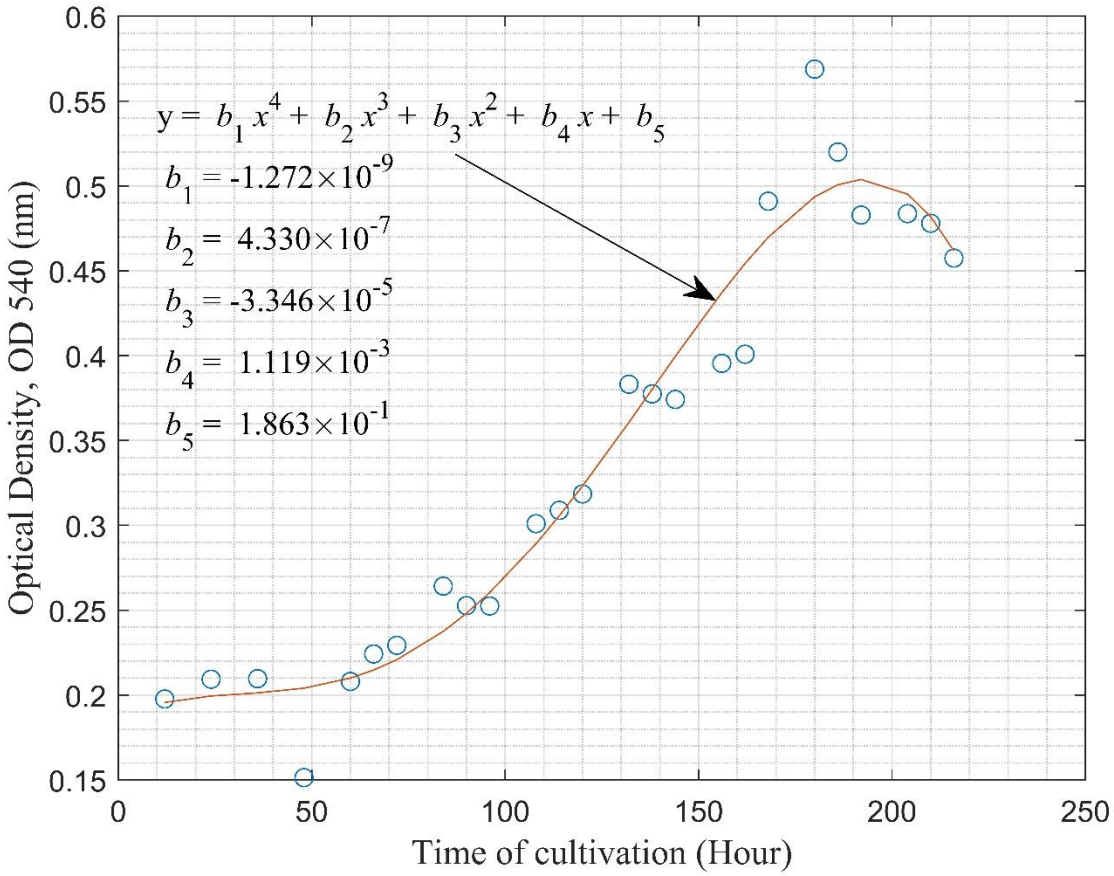

Fig. 6. Optical density as a function of cultivation time for Babolsar tests.

Table 1. Absorption Amount of CO_2 Measured Three Times per Day over a Six-day Period (Tehran test).

Day	Hour	Input CO_2 (ppm)	Output CO_2 (ppm)	CO_2 absorption (ppm)	Input temperature (°C)	Volume (liter)	Evaporation (liter)
1	10.00	1091	962	129	26.0	4.16	-
	13.00	1303	1224	79	25.8	5.16	-
	16.00	1109	1033	79	24.1	-	-
2	10.00	868	655	213	24.2	5.00	0.16
	13.00	1307	1228	80	25.4	-	-
	16.00	1445	1386	59	26.6	-	-
3	10.00	864	704	160	24.5	4.91	0.09
	13.00	870	697	173	24.8	-	-
	16.00	1102	950	152	24.6	-	-
4	10.00	895	722	173	23.9	4.83	0.08
	13.00	1017	791	226	24.7	-	-
	16.00	1023	957	66	25.1	-	-
5	10.00	1121	546	576	24.5	4.79	0.05
	13.00	1097	619	478	25.7	-	-
	16.00	1167	844	323	26.3	-	-
6	10.00	1189	512	677	24.8	4.70	0.09
	13.00	1291	709	582	25.9	-	-
	16.00	1201	789	412	26.6	-	-

Table 2. Absorption Amount of CO_2 Measured per Twelve Hours over a Nine-day Period (Babolsar test)

Hour	Input CO_2 (ppm)	Output CO_2 (ppm)	CO_2 absorption (ppm)	Input temperature (°C)	Output temperature (°C)	Volume (liter)	Evaporation (liter)
0	611	801	-190	24.0	24.8	5.00	-
12	848	821	27	23.8	24.4	5.00	-
24	960	897	63	23.4	24.5	4.92	0.08
36	908	812	96	23.3	24.3	4.92	0.00
48	925	807	118	23.5	24.2	4.89	0.03
60	689	595	94	23.8	24.6	4.89	0.00
72	683	494	189	24.2	24.8	4.88	0.01
84	668	487	181	24.7	25.5	4.86	0.02
96	631	491	140	25.1	25.8	4.85	0.01
108	622	401	221	24.8	25.5	4.84	0.01
120	730	513	217	25.1	26.0	4.82	0.02
132	649	497	152	24.5	25.2	4.81	0.01
144	565	566	-1	24.3	25.1	4.79	0.02
156	655	451	204	25.5	25.7	4.79	0.00
168	722	574	148	23.9	24.3	-	-
180	716	482	234	23.9	24.6	4.76	0.03
192	712	602	110	24.4	24.8	4.68	0.08
204	512	458	54	23.6	24.5	4.64	0.04
216	703	594	109	24.1	25.3	4.62	0.02