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Original Research Article

Algae Façade for Reducing CO_2 Emission and Mitigating Global Warming
(Case Study: Tehran Enghelab Street)

Saeed Haghir*[1], Leila Tashakori[2], Hamidreza Rezazadeh[3], Ferial Ahmadi[4]

1. Associate Professor of Architecture, Faculty of Fine Arts, University of Tehran, Iran.
2. M.A. in Landscape Architecture, Faculty of Fine Arts, University of Tehran, Iran.
3. Ph.D. Candidate of Architecture, Department of Architecture, Faculty of Architecture and Urbanism, Art University of Isfahan, Isfahan, Iran.
4. Department of Architecture, Faculty of Art and Architecture, University of Mazandaran, Babolsar, Iran.

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Abstract
Problem statement: Walls along urban streets are one of the most prominent aspects of the architectural design affecting the aesthetics of urban landscapes. Hence, these walls are environmental elements capable of elevating the aesthetics and visual qualities of urban spaces. One of the main issues in big cities is the rise of local temperatures due to high concentrations of carbon dioxide. Meanwhile, quality control initiatives are mainly focused on the sources emitting carbon dioxide.Moving toward environmental architecture and urban design, adjusting the design strategies, and inventing new solutions to restore balance to nature while satisfying today’s human needs has resulted in the increasing development and use of vertical green systems throughout the world.

Research objectives: the objective is to provide a solution for integrating microalgae bioreactors with building façade to absorb carbon dioxide and to decrease the air temperature while preserving the identity and integrity of the building.

Research method: Considering the novel and multidisciplinary nature of this study, a compound methodology is required. This is a descriptive-analytic practical study. Hence, using bibliographic documents and scientific studies at first, microalgae are defined and examined for absorbing air pollution. Then, the façade of Enghelab Street is chosen as a polluted urban center. Finally, after identifying relevant surfaces for installing bioreactors, the façade of Enghelab Street is redesigned.

Conclusion: Using microalgae as alive microorganisms capable of absorbing carbon dioxide, and integrating them with building facades by bioreactors, converts these walls to photosynthetic surfaces. These surfaces respond to climate changes, improve the passive thermal performance of the building, transform an ordinary building into an alive building, and convert the walls into energy-producing factories.

Keywords: *Urban Design, Air Pollution, Tehran Enghlab Street, Biological facade, Microbiology.*

Corresponding author: saeed.haghir@ut.ac.ir , +989124434927

Introduction

The increase of carbon dioxide in the atmosphere is in close relation with climate changes, especially the issue of global warming (Malik, Lan & Lenzen, 2016). Urban areas are estimated to consume more than two-thirds of the world's energy while producing more than 70 percent of the carbon emissions (IEA, 2012). Hence, reducing carbon emissions is crucial to combat the issue of global climate change (Wang, Liu, Zhou, Hu & Ou, 2017), and doing so while maintaining the pace of economical developments is a two-sided challenge for states

Therefore, researches on factors affecting carbon efficiency become of increasing importance (Li, Zhou, Wang & Hu, 2018). The wall of a building is a boundary between inside and outside space. This boundary is expected to control external factors and use environmental capabilities efficiently, that provides comfort for the beneficiaries, but also has a critical role in reducing urban pollutions.

Research Problems

This study deals primarily with the main question that how much adding bio-façade (bio-reactive façade containing algae) to the building's façade reduces the carbon dioxide in the air, and what effects it has on the urban landscape.

Researches on carbon emissions and ways to tackle it are mainly concerned about the emitting sources and seem to overlook the existing carbon dioxide. While recognizing the status quo and limiting the research scope, this study proposes three questions to reach its objective in providing a modern, innovative, nature-inspired and sustainable solution:

1. How nature and architecture can work together to absorb and reduce carbon dioxide?
2. What is a bio-façade and how is it added to urban facades?
3. How effective is bio-facade in improving the quality of urban spaces and streets?

Methodology

As for the ultimate goal, this study is a practical research utilizing literature reviews, field studies, and numerical computations. The research process is divided into four main sections. In the first section, the concept of using micro-algae in conjunction with building facades is introduced and explained using scientific resources and bibliographic data. Section two is field research. The south façade of Enghelab Street is imaged, and surfaces capable of installing bio-reactors are identified. Then, using the obtained dimensions in previous researches and matching them with technical aspects of bioreactors, the proper dimensions for designing a bioreactor are obtained. And finally, by using the base dimensions of a bio-reactor as a module, the south façade of Enghelab Street is designed and the amount of carbon dioxide absorption and reduction in this urban passage is estimated using mathematical and numerical operations. Furthermore, after professional interviews with related companies and research centers, Chlorella is identified and selected as the most suitable micro-algae, due to its abundance in algae resources of the Persian Gulf, high resistance to critical and stressful cultivation processes, availability, low-price compared to other micro-algae, fast-paced growth and reproduction, resistance to temperatures up to 45 degrees (suitable for hot and arid climates), and the high absorption of carbon dioxide.

Theoretical foundations and Research background

• Carbon dioxide and its current global status

The average air temperature rising due to the increase of greenhouse gases in the atmosphere is resulting in climate change. Among the gasses and compounds contributing to climate changes and global warming, carbon dioxide is identified as the most abundant and most critical compound and is used as a benchmark to assess and compare other types of gasses and compounds involved in this phenomenon. Studies show that carbon emissions between 1970 and 2007 exhibit an 80 percent increase, reaching from 21 to 38 gigatons (IPCC, 2006). In 2015, Iran stood in ninth place in carbon-emitting countries, and in the Paris Summit, committed to a 4 percent reduction until 2030 (Shafi'pour Motlaq & Tavakkoli, 2016). Therefore, controlling and managing greenhouse gasses is listed as one of the current century's critical challenges.

- **Nature in architecture as a way of controlling carbon dioxide**

Currently one of the eminent concerns of city officials and experts all over the world is the absorption and reduction of carbon dioxide in the air, which has become a global crisis over the last few years. Accordingly, numerous researches are made and different methods are proposed (Lal, 2008; Pachauri et al., 2014'; Zhao and Su, 2014' Zhang, 2015; Elliot, 2016) that can be broadly categorized as biotic or abiotic methods. Abiotic methods include the absorption of carbon dioxide using physical and chemical alterations and engineering techniques, and biotic methods use natural elements including water, plants or microorganisms. Unfortunately, abiotic methods, although having high speed in stopping and controlling the carbon dioxide, are not sustainable and have adverse health impacts due to the usage of chemicals. In contrast, biotic methods have a slow rate of controlling and absorbing carbon dioxide but they are cheap and useful for other environmental processes, have the least impacts on human health and do not need any special technologies (Lal, 2008). Thus far, many biotic methods are proposed to absorb carbon dioxide using oceans, the earth, and plants (Elliot, 2016). Among them, the absorption of carbon dioxide using plants is the fastest, cheapest, most sustainable, and most effective method, and unicellular plants including moss, lichen, and microalgae, perform better due to their simple structure and high surface-area-to-volume ratios (Rezazadeh, 2019). Besides, microalgae have specific cultivation and preservation features making them capable of integration with building facades, allowing plain walls and urban facades to be converted into bio-facades.

- **Using microalgae in building facades**

Microalgae are live plant microorganisms being unicellular in their simplest form (Pearson, 1995). Compared to multicellular plants, these microorganisms are very efficient in absorbing air pollution due to their high surface-area-to-volume ratio (Alabi, Bibeau & Tampier, 2009). In the process of photosynthesis, microalgae absorb carbon dioxide from air or water to produce 60 to 75 percent of the oxygen needed for human and animal life (Wolkers, Barbosa, Kleinegris, Bosma & Wijffels, 2011). Microalgae photosynthesis ability is 10 times higher than grown trees and grass, such that 1.8 kilograms of carbon dioxide is absorbed to produce one-kilogram microalgae biomass (Elrayies, 2018).

Since urban walls and buildings have large surfaces exposed to polluted air, integrating microalgae in a building facade to form a bio-façade, not only helps in absorbing air pollution, but also converts the wall into a photosynthetic surface responding to climatic changes, improving the passive thermal performance of the building, transforming a typical building into a healthy and alive building (ibid.), and ultimately converting building walls into energy-producing factories (Cervera-Sardá, Gómez-Pioz & Ruiz-de-Elvira, 2014). To integrate microalgae with a building façade, it is essential to use a container called a bioreactor to provide the cultivation and reproduction environment (Mata, Martins & Caetano, 2010). Considering the categorization of bioreactors and their ability to attach to building walls and façades, the closed system (Wolkers et al., 2011) is the best choice. By displaying the external changes in the cultivation environment and reflecting it in the building façade, this results in variety and dynamic urban landscapes.

- **Closed bioreactors**

Having a high surface-area-to-volume ratio is the main factor in the mass production of microalgae due to the optimal and uniform distribution of light throughout the cultivation and photosynthesis processes. Hence, the shape and geometry of bioreactors have an integral role in the efficiency of the system (Kunjapur & Eldridge, 2010). Accordingly, planar bioreactors can help to achieve this result in the construction industry by providing the right geometry and high surface-area-to-volume ratio.

The right thickness of a bioreactor is determined by the distance traveled by light rays through the microalgae cultivation container, so that no dark spots remain, and happens to be 15 mm based on numerous studies (Degen, Uebele, Retze, Schmid-Staiger & Trösch, 2001), while the optimal thickness for bioreactors is estimated to be 5 to 6 cm (Marsullo et al., 2015). Since the reproduction of microalgae is directly dependent on the mixing process in the cultivation environment, planar bioreactors work well by propagating air bubbles from the deepest sections, having a natural combination in the cultivation environment, and avoiding the accumulation of soluble oxygen (Kumar & Goyal, 2011). Orientation with respect to sunlight is a vital factor in these systems. According to Sierra et al. (2008), ea st-west orientation for areas with more than 35 degrees of latitude and north-south orientation for areas with less than 35 degrees of latitude is essential. In a research done by Slegers (2014), it is shown that the orientation of planar bioreactors in high latitudes (east-west) has a 50 percent difference in production and system output compared to low latitudes (north-south). Hence, we can argue that south and south-west orientations for planar bioreactors in high latitudes are the optimal orientation for building facades (Elnokaly & Keeling, 2016).

• Essential requirements and technical details in designing bio-facades

To create an optimal bio-reactor, consistent system inputs from providing sources, proper technical details are needed to obtain the desired output. Inputs, providing sources, technical details, and outputs are listed in table 1.

• Benefits and impacts of using microalgae bioreactors in building façades

In addition to absorbing carbon dioxide, impacts

Table 1. Inputs, providing sources, technical details, and outputs. Source: Authors.

Inputs and Outputs	Providing sources	Technical details
Inputs	Carbon Dioxide	Providing the carbon dioxide required for microalgae from output gasses of plants, industries, factories, polluted air, etc. It is required and rational to have a carbon dioxide producer in the proximity of the project. Otherwise, the required carbon dioxide should be obtained from the building (U.S. DOE, 2010). Furthermore, equipment such as carbon dioxide scruber on the building can solve the issue of carbon dioxide reservation and transfer. The carbon dioxide scruber device requires electricity, which is sustainably provided by a wind turbine on the site.
	Water	Microalgae can grow in different types of water. The water used in this system is reusable, hence the water cycle in the bioreactor can be designed as a closed system (Elrayies, 2018). Water sources include seawater, rainwater, salty water, and even wastewater and polluted water.
	Nutrients	Graywater and blackwater from buildings. The required nutrients can be provided by the building's wastewater.
	Microalgae	After the cultivation of microalgae in bioreactors, preserving them in a controlled temperature until utilization is critical. Temperature control containers are used in this stage
Outputs	Heat	Bioreactors convert sunlight to heat, acting as heat insulation. A fraction of this heat is needed in the cultivation of microalgae but extra heat should be absorbed by thermal converters.
	Microalgae Biomass	Having a refinement system like a centrifuge device is essential to extract biomass and other products from microalgae. The extracted oil is used as biofuel, microalgae biomass is used for electricity, and the residual water is reused in the cultivation process.
	Oxygen	It is essential in bioreactors to remove soluble oxygen using liquid gas devices (Machado et al., 2013). Furthermore, the oxygen gas is collected through special equipment (Suali & Sarbatly, 2012).

include producing some of the energy needed for the building through biomass, controlling the amount of light entered, controlling the views and landscapes, thermal insulation, environmental sustainability, reducing overall costs of the building, and aesthetics (Elrayies, 2018), which are briefly explained in table 2.

As stated in table 2, one of the main debates around using microalgae in buildings is the costs of implementation and maintenance. According to estimates, a total of 30 euros should be considered for one meter squared of building surface (Torgal, Buratti, Kalaiselvam, Granqvist & Ivanov, 2016). The numbers shown in table 3 emphasize the importance of reducing costs. Hence, many researchers are working on these costs (Issarapayup,

Table 2. The benefits and impacts of microalgae bioreactors in building façade. Source: Authors.

Benefits and impacts	Details
Producing energy through biomass	Biofuel (biomass) is a new type of renewable and sustainable energy having zero impact on global warming and climate change (Elrayies, 2018). Microalgae as a sustainable biomass source, convert 50 percent of the fats stored in their cells to pure oil used in bioenergy sources (Edwards, 2008). It is worth noting that the biomass produced in the engine room is extracted using centrifuge devices and stored in preinstalled containers.
Controlling the light	Green microalgae absorb red beams of sunlight, so the bioreactor can provide shade for the building and impact the amount of light entered (Pagliolico et al., 2017). Thicker microalgae in the bioreactor result in less light entering the room (Oncel et al., 2016; Elnokaly & Keeling,2016).
Controlling the view and external appeal	Adding bioreactors to the building impacts on the visual connection of inside and outside space, and improves the external features of the building (Decker et al., 2016; Pagliolico et al., 2017). Furthermore, daily and seasonal color variations of microalgae due to the maturity level, and the dynamic nature of bioreactors due to moving bubbles inside the panels, result in an attractive and variable façade for the building.
Thermal performance	Bioreactors absorb sunlight beams and create shades (Decker et al, 2016; Flynn, 2016), resulting in a cooler inside space on sunny days. The amount of shading correlates with the thickness of microalgae. This process can be described as a symbiotic relationship between the bioreactor and the building (Pruvost et al., 2016).
Acoustic performance	The physical structure of microalgae allows them to diffract and modulate audio waves. As before, the thickness of microalgae has a direct relation with the acoustic performance of the bioreactor (Sarda & Vicente, 2016).
Environmental sustainability	Microalgae with their many functions including carbon dioxide absorption, wastewater treatment, and producing oxygen, have an advantage to other renewable energy sources.
Investment costs (initial installation)	Even though closed bioreactors increase the efficiency of microalgae by providing detailed control and surveillance features, the high cost of implementation is their biggest drawback (Kunjapur & Eldridge, 2010). These expenses are well paid off with long-term energy savings and other benefits provided for the building and the environment (Schiller, 2014). According to reports, the investment on these devices returns in 9 to 13 months (Sarda & Vicente, 2016).
Aesthetics	The concept of beauty and aesthetics is highly relative to the context, but combining alive microorganisms with building walls will improve the aesthetic features. Microalgae with their dynamic and fluid physical and chemical nature can bring life to dull and boring building walls (Elrayies, 2018).

Table 3. The costs of making, installing and maintaining bioreactors. Source:Torgal et al., 2016.

The area of the bioreactor (m^2)	100	200	500	1000	5000
Total cost (euros)	10060.5	12573.9	16343.9	22627.3	77894.5
Cost per m^2 (euros)	100.6	62.9	32.7	22.6	15.6

Powtongsook & Pavasant, 2011), various aspects of microalgae, and the design of bioreactors.

- **Urban landscape**

In addition to socio-economic factors, urban morphology is increasingly considered due to its potential role in preventing climate changes (Li et al., 2018), and Urban facades are no exception. One of the key issues in metropoles like Tehran is the crisis in urban landscapes. This crisis can be examined in micro and macro scales. Many efforts concerning urban landscapes are made in macroscale, but microscale impacts are almost always overlooked (Jafari & Nili, 2019). Aside from visual disturbances, it should be noted that environmental pollution in urban spaces, especially carbon footprint in urban centers is increasing, and attention to both micro and macro scales is of great importance.

- **Aesthetics of urban façade**

The aesthetic value of streets in the urban landscapes is distinct from other physical elements of a city. Streets, having a linear structure and acting as pathways require specific details in defining their identity (Zekavat, 2006). Streets comprise of various architectural elements. Their beauty in the physical form require different elements to work in harmony and create a continuous flow. Façade is one of the most effective elements affecting the visual quality of a building, thus the quality of urban spaces. So it is considered as one of the elements elevating the visual quality and aesthetics of urban spaces.. Since today the urban facades are developed with no regard to aesthetics and architectural principles, they demand revision (Mousavi Sarvineh Baghi & Sadeghi, 2016).

- **Façades driving aesthetics and improving air quality**

The external envelope of a building – as one of the most effective aesthetical elements in the urban landscape and also the junction of interior and exterior space – plays an important role in defining the urban landscape (Shirazian, Hosseini, Norouzian Maleki, 2014). One of the main approaches in architecture and urban design is seeing nature as a role model and solution to mitigate environmental issues. Nature's response to human issues is proven since the beginning of time, and the survival of man and manmade environment rely on the protection and continuation of the natural environment. Hence, architecture plays an integral role in improving the quality of life and achieving sustainability by absorbing carbon dioxide and converting urban elements into tiny alive systems. Identifying the potential urban surfaces capable of installing carbon dioxide absorption panels using alive microorganisms (microalgae) is crucial. Therefore, in this section, the surfaces on Enghelab Street – as an important axis in Tehran having a high amount of traffic and also large amounts of carbon dioxide – are examined for installing microalgae bioreactors.

Discussion

- **Building facades of Enghelab Street**

In many metropoles across the globe, the physical structure of surfaces along with concentrated human activities result in high temperature of city centers and adverse climate change such as heat islands and pollution, which leads to discomfort of the habitats, and impacts urban management initiatives for controlling air pollution. Enghelab Street as an urban center is no exception. In addition to the issue of air pollution, problems and inconsistencies of facades have resulted in an unpleasant and unsightly urban landscape. One solution to the low quality of air and the unsightly landscape is installing microalgae panels that absorb and reduce carbon dioxide while improving the urban landscape. Movement in the building façades improves the aesthetic features of the city, and microalgae's structure and their dynamic physical and chemical nature helps in bringing life to dull and boring building walls (Elrayies, 2018) and improving the quality of urban landscapes. Accordingly,

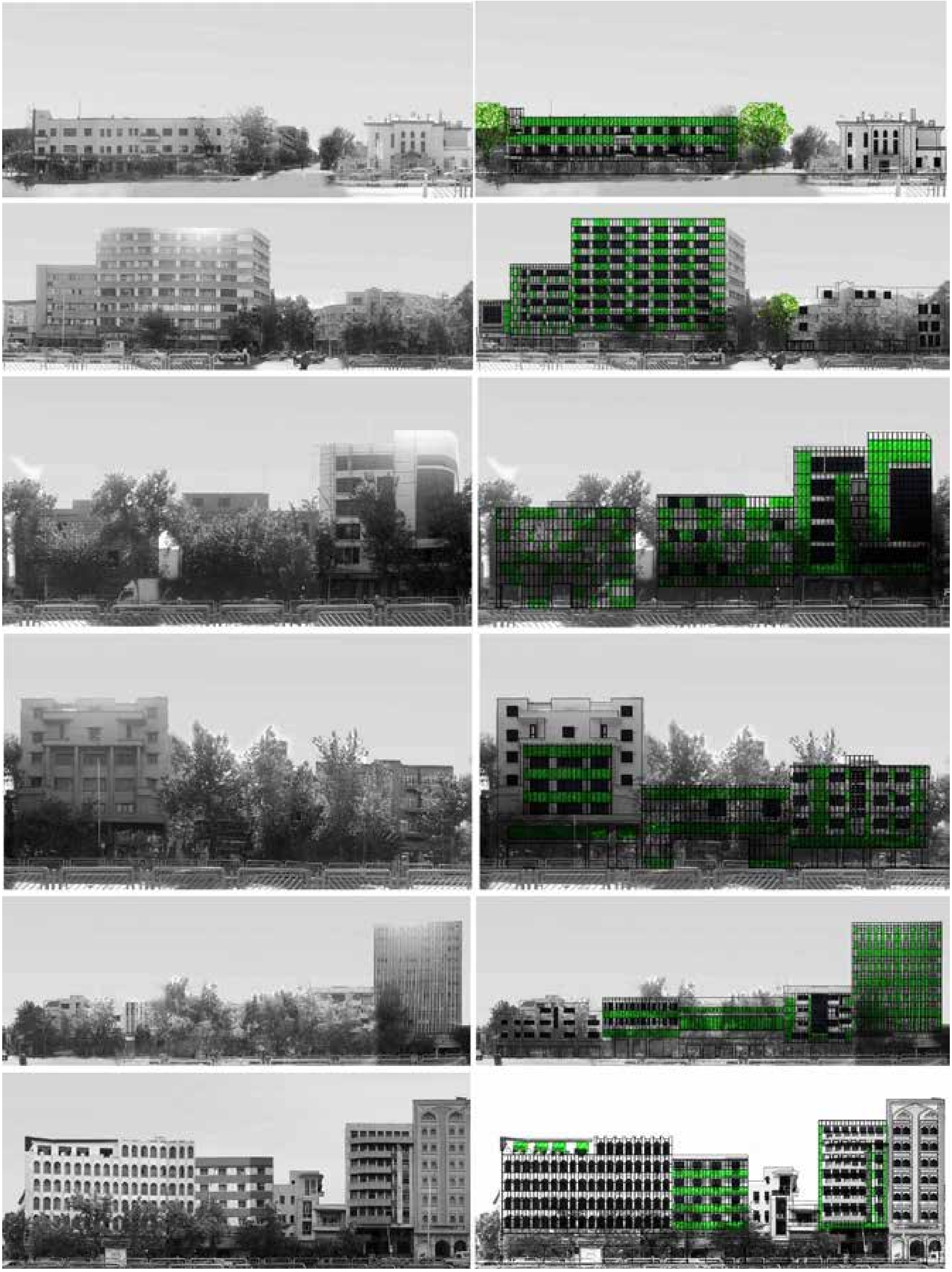

Fig. 1-a. Comparing the south façade of Enghelab Street with and without microalgae panels. Source: Authors.

Fig. 1-b. Comparing the south façade of Enghelab Street with and without microalgae panels. Source: Authors.

photos were taken from the south façade of Enghelab Street. the area of surfaces capable of installing bioreactors (useless and without opening) was estimated to be 6900 m^2 (Fig. 1-a & B). Considering the geometry and dimensions of bioreactors, the total area of bioreactors and the number of panels were calculated.

- **Geometry and dimension of bioreactors**

The most important factor in the efficiency of any bioreactor is having a high surface-area-to-volume ratio. Planar bioreactors have the largest area exposed to light and the shortest distance for the light to travel through, which makes them very effective compared to other types of reactors. As mentioned previously, 15 mm is identified as the optimal thickness, since it leaves no dark spots inside the reactor. Furthermore, in research done by Kim and Todorovic (2013), the optimal height-to-width of a bioreactor is estimated to be 2.5. These ratios result in the lowest pressure of the internal fluid and the lowest thermal waste in bioreactors. Finally, using the standard dimensions of windows provided by The Special Committee of Architecture, the height of 100 cm, the width of 40cm (2-to- 5 ratio), and the thickness of 16mm for the cultivation layer was chosen for a commercial panel. To install the bioreactor on the building, a support structure attaching to all types of facades is used. This structure holds the bioreactor while preventing the tensions of the internal fluid or external forces like wind, helping in the sustainability of bioreactor on the façade (Fig. 2).

- **Bioreactor performance**

To cultivate the Chlorella microalgae using sea salt and tap water, a 4-liter cultivation environment with 25ppt saltiness was prepared, and 1 liter of Chlorella stock was added to the container (1-to-5ratio), which then transferred to the bioreactor in sterile conditions. The cultivation environment was sterile, and the window received 1000 lux lighting for 12 hours using artificial light and 12 hours with automatic timer light (Fig. 3). The temperature was set to 25 to 27 degrees throughout the experiment. The air was put through the panel using a central

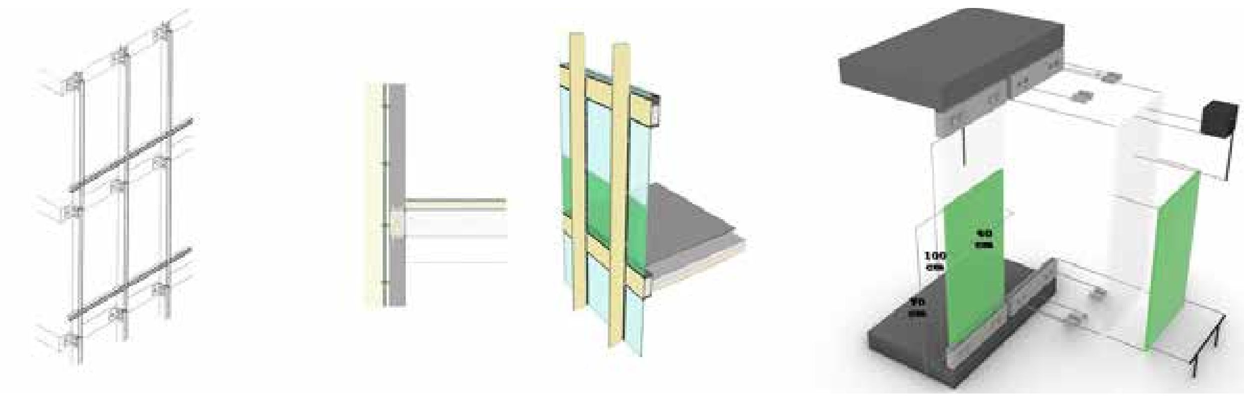

Fig. 2. Dimensions of the bioreactor, the supporting structure and attaching the bioreactor to the façade. Source: Rezazadeh, 2019.

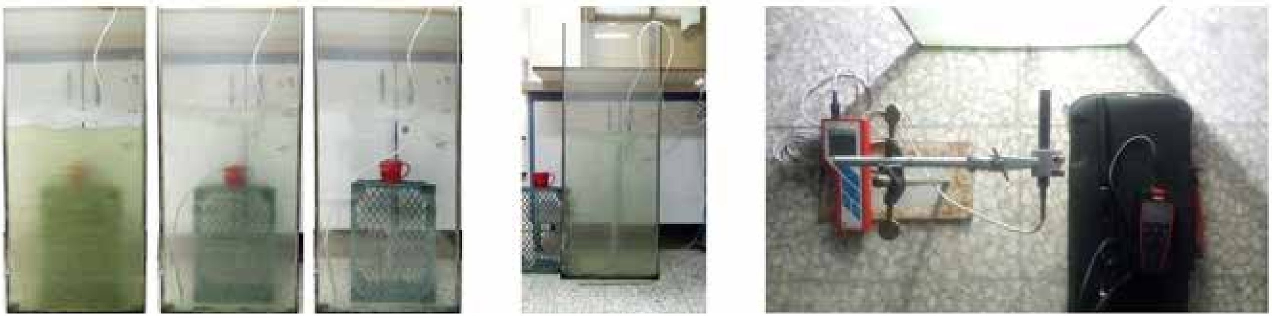

Fig. 3. the manufactured bioreactor and the equipment used in the testing process. Source: Authors.

aquarium pump that was installed below the bioreactor and uniformly pumped 3. 5 liters of air in every minute. The air bubbles move from bottom to top, letting microalgae to absorb carbon dioxide and produce oxygen in the photosynthesis process. This process also prevents microalgae to sediment inside the bioreactor. On top of the bioreactor was a 20cm to 30cm space to accumulate oxygen gas, which was transferred inside or outside the building using a suction pump. The soluble oxygen was absorbed by an absorber device and was accumulated on top of the bioreactor to be used in the air conditioning system. carbon dioxide thickness was Measured in 6 days at 10 AM, 1 PM, and 4 PM, considering the rush hours in Tehran. The location of the experiment was Vali'asr square which is one of the most polluted areas of the city, and also is in the proximity of the air quality station in Fatemi Street. After designing and manufacturing the bioreactor based on technical guidelines, it was replaced with an ordinary window in the experiment room south of the square. Throughout the experiment, all the data was collected from this point and place to minimize the impact of placements on input variables. It should be noted that during the daytime, there is no need for artificial lighting by lamps, and artificial lighting was only done in the nighttime to continue the ongoing process of microalgae photosynthesis. Accordingly, the lighting period was set from 10 PM to 10 AM, so the artificial lighting ended at 10 AM and 4 PM was midway in the dark period. The thickness of carbon dioxide and the amount of absorption by the bioreactor was measured with a CO_2 gauge.

After examing the daily average amount of absorption, the following numbers were obtained: 6.6% in day 1, 9.7% in day 2, 17.1% in day 3, 15.8% in day 4, 40.7% in day 5, and finally day 6 with 45.4% had the highest amount of absorption. The total average for 6 days equals 22.55%. hence, 5040 liters of air containing carbon dioxide and carbon monoxide entered the bioreactor and 1136.[5] liters of clean air exited from it. After the 6 days, all the contents were removed by a discharge pump and transferred into the central engine room in the basement. Using a centrifuge, biomass was separated from the cultivation environment and put aside to be used as fuel. Then the microalgae were added to the cultivation environment with the aforementioned ratio, and the system was set for another 6 days, maintaining the transparency of the bioreactor and the amount of vaporized water at a proper and uniform level. Using modules on the south façade of Enghelab Street, 2666 bioreactors can be fitted with a total of 1066 m^2. As in figure 1, these numbers are obtained with regard to architectural and geometrical features of the original building to add beauty and integrity while avoiding damage to its identity.

Conclusion

This study proposes a solution to integrate microalgae bioreactors with building facades of Enghelab Street as a prominent urban pathway. This process preserves the overall identity and integrity of the street while absorbing carbon dioxide and decreasing the local temperature of the surroundings. Combining bioreactors with building facades creates a unique opportunity by converting these walls into photosynthetic surfaces responding to climate change, improving the passive thermal performance of the building, transforming an ordinary building into a healthy and alive one, and finally converting the building walls into energy-producing factories. After installing the bioreactor on the façade, the average daily absorption of carbon dioxide in the 6 days was 22.55% which clearly shows that if a substantial amount of urban walls and facades is covered with this bioreactor, it will sustainably and considerably reduce the amount of carbon dioxide in a short period; hence, taking an effective step forward in improving the air quality, and preserving and sustaining the urban environment.

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