buildings

Article

Exploration for Spatial Sustainability of Microalgae Façades Based on Mock-Up Cultivation Settings

Seung-Ju Choe [1] and Seung-Hoon Han [2,*]

[1] Graduate School, Chonnam National University, Gwangju 61186, Korea; 216473@jnu.ac.kr
[2] School of Architecture, Chonnam National University, Gwangju 61186, Korea
* Correspondence: hshoon@jnu.ac.kr; Tel.: +82-62-530-1646

Abstract: Microalgae are third-generation biomasses that can be used to extract bio-fuel with various advantages from an ecological perspective. In addition, since it is cultivated in an underwater space, it can be used as a microalgae culture space by using building facades. Architectural applications of microalgae are being carried out from various points of view in other countries such as America, Israel, and Germany. As a result, successful cases (such as Germany's BIQ House) are emerging. However, research studies related to microalgae facade are mainly conducted in terms of culture environment and efficiency. The degree of inflow concerning external resources for a microalgae facade remains unclear. The question concerning how the environment of an indoor space where microalgae facade is installed could be changed is unclear too. Thus, the objective of this study was to analyze the impact of the space in which the microalgae facade was installed from the perspective of the lighting environment. This study also examined effects of creating a lighting environment compared to existing windows, applicable space, and supplementary points through mock-up tests on microalgae facade. As a result, it was found that the standard microalgae facade suggested by the Korean Intellectual Property Office (KIPO) could inflow 22.7–41.3% of illumination compared to general windows. If the analysis result is compared with Korean Standard A 3011 (Normal), the microalgae facade can only be applied to spaces that do not have natural light such as 'warehouses' and 'stairs'. Accordingly, it is concluded that if the microalgae facade is to be used creatively, the thickness should be thinner than the standard of patent to set the standard of comfort and consider the user's comfort in the design stage.

Keywords: microalgae facade; daylighting; illumination; visible light transmittance; spatial sustainability

check for updates

Citation: Choe, S.-J.; Han, S.-H. Exploration for Spatial Sustainability of Microalgae Façades Based on Mock-Up Cultivation Settings. *Buildings* **2022**, *12*, 304. https://doi.org/10.3390/buildings12030304

Academic Editor: Manuel V. Castilla

Received: 30 December 2021
Accepted: 3 March 2022
Published: 4 March 2022

1. Introduction

1.1. Background & Goals

Bioenergy is being highlighted as a new green and carbon neutral energy that can reduce carbon dioxide. Microalgae are classified as third-generation biomasses. They are more environmentally friendly and efficient than grain and wood in various aspects such as raw material production cost, required time, production volume, and carbon fixation effect [1]. Therefore, research on microalgae-related culture and energy harvesting technology as a future eco-friendly energy resource in the field of bioenergy is currently in progress. Huge microalgae plants are being built and operated in developed countries including the United States and Israel [2]. According to the 'World Energy Outlook 2014' survey and research report published by the International Energy Outlook, it is predicted that the use of bioenergy will account for 19% of the total energy market in 2040 [3].

In addition, since microalgae are cultured in water, various culturing methods have been proposed using various types of photobioreactors. Among them, the vertical type has the advantage of culturing microalgae in a vertical plane, as few horizontal areas are required for culturing [3]. There are some examples in which the function of culturing microalgae is given to the building facade, window, or urban component by using a vertical photobioreactor. Representative cases include Germany's BIQ house, UK's Photo Synth Etica, and Mexico's Bio Urban Project. They suggest the possibility of bioenergy production using buildings by integrating functions of a building's facade and photobioreactor [4–6].

However, major research topics in this field have attracted interest, including technological aspects such as the creation of a microalgae culturing environment and the increase in culturing efficiency. On the other hand, the indoor environment which changes according to the installation of microalgae facades has been rarely studied. Humans can use a building facade to protect themselves from the external environment. If necessary, a part of the external environment can be introduced into the indoor space to create a living environment. In particular, in terms of the light environment, a building facade is an element that must be analyzed and designed from a planning point of view such as natural lighting and lighting planning. It is classified as an environmental factor with the greatest influence on the indoor lighting environment [7,8]. Considering these points, it can be said that in order for microalgae facades to be applied to buildings, studies considering the indoor environment should be conducted concurrently.

Accordingly, this research performed a mock-up test to determine the indoor influence of microalgae facades in terms of lighting environment based on nationally certified microalgae window specifications. Based on collected data, different types of buildings and indoor spaces that could be applied to microalgae culture as building envelopes were identified.

1.2. Steps of Research

This research consisted of several steps to analyze changes of an indoor lighting environment according to the application of a microalgae facade's architectural space and to identify the applicable building and indoor space types.

As the first research step, indoor surrounding factors related to windows and typical daylighting environment assessment methods were identified for microalgae window specifications and indoor lighting environment analysis for the application of microalgae facades.

In the second step, a mock-up monitoring test was planned based on previous researches to determine changes in the inside daylighting environment according to the installation of microalgae facades. Lighting environment monitoring data were collected using presented methods.

Finally, collected data were compared and analyzed with Korean Industrial Standard A 3011 (KS A 3011) to suggest types of buildings and indoor spaces suitable for microalgae facades. Supplementary points for expanding the applicability of microalgae facades were reviewed. The research flow consisting of these steps is shown in Figure 1.

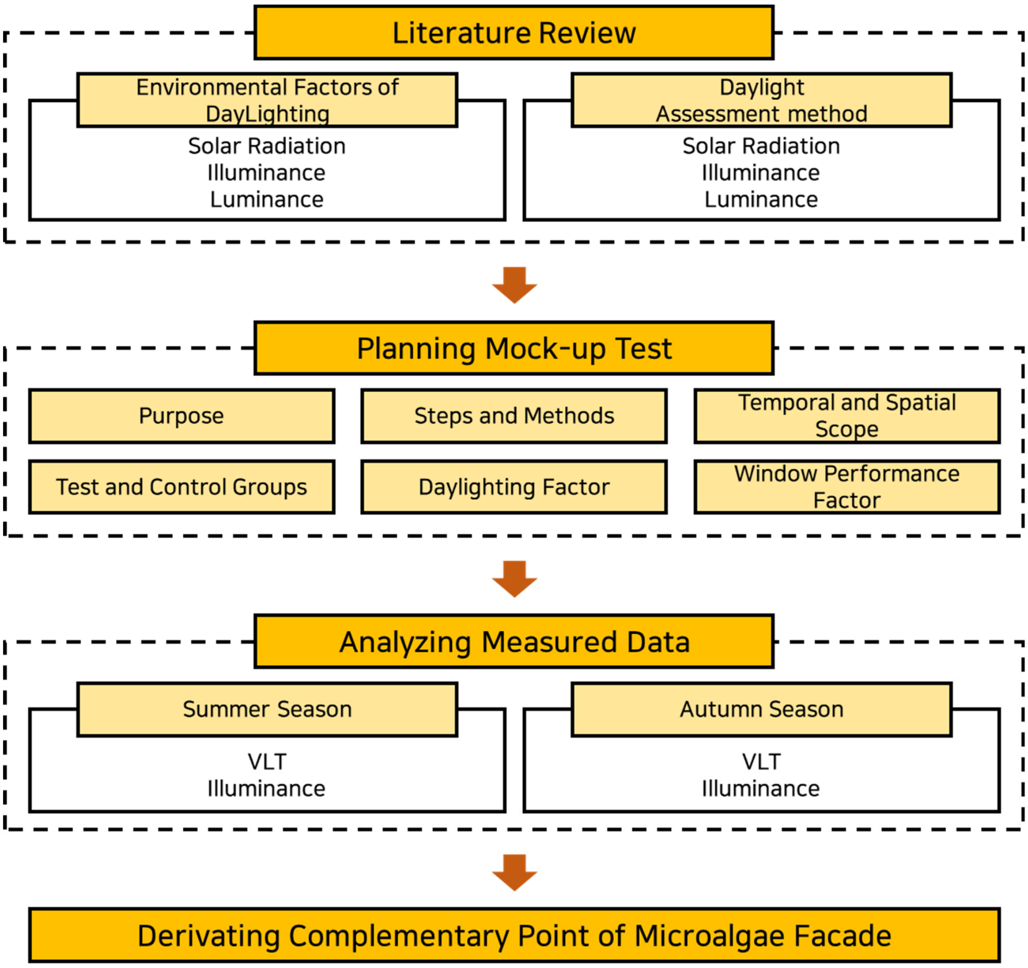

Figure 1. Research flow.

2. Literature Review

2.1. Factors Related to Indoor Natural Lighing Environment

2.1.1. Solar Radiation

Solar radiation is the radiant energy emitted from the sun when it reaches the earth's horizontal ground. In this situation, the amount of energy reaching the earth's surface is called insolation. It is expressed as W/m^2 and MJ/m^2 [9]. In general, when solar radiation energy flows into the earth, its energy is reduced by dust and water vapor distributed in the atmosphere. When there are more these particles, less solar energy will reach the ground [10].

Solar radiation is one of the major variables of an indoor thermal environment. The perspective of utilization of solar radiation varies depending on the location of the building and the local situation. In an area with lots of solar radiation, it is necessary to shield the insolation in order not to increase the temperature of the inside. Designers in this area can plan louvers and eaves in building design in order to block heat from outside. Conversely, high humidity can be created in areas with low insolation. In such cases, mold may grow indoors, which can adversely affect the user's health and durability of the building [11]. Therefore, in such an environment, a technique that minimizes the phenomenon of discharging heat from the indoor space to the outside is applied to the building.

Solar heat gain coefficient (SHGC) is a major performance factor of windows related to solar radiation. SHGC refers to the amount of insolation coming in through windows. It is calculated as the sum of solar energy directly entering from the outside and solar energy absorbed and emitted from glass. If a window's SHGC is higher, it is easier to have inflow of solar radiation from the outside into the room [12].

2.1.2. Illuminance

Illuminance refers to the amount of light per unit time that an object receives when light flows into an object from a specific light source. Its unit is lux (lx) or candela (cd). Korean illuminance standards are written in lux. Illuminance is affected by the brightness of the light source and the distance from the light source [13].

Illuminance is classified as the most important environmental factor in acquiring visual information of an object, such as color and texture. In modern architecture, only the possibility of delivering visual information has been judged. The common perception is that the higher the illuminance of the indoor space, the better. However, as the importance of visual environment has increased, a design that provides an appropriate illuminance environment in consideration of the use, type of space, and tendency of users has become an essential element. According to the tendency, glass with appropriate physical properties is used depending on the use of space [14].

In terms of visible environment, visible light transmittance (VLT) exists as typical window performance index related to illuminance. VLT refers to the percentage of visible light that can enter through a window. In general, when a window has a low VLT performance, it is difficult to see outside through the windows. The amount of light that enters in the room is decreased. Therefore, when a window with a low VLT is applied to a building, there is a disadvantage in that artificial lighting must be used even in daylight hours. Due to this problem, it is necessary to set the VLT of the window by understanding the use of the space and activities carried out inside.

2.1.3. Luminance

The definition of luminance is the amount of light reflected from the object flow into human eye. The unit of luminance is cd/m^2 or nitro (nt). Since luminance can judge user comfort such as glare, the International Commission on Illumination (CIE) guidelines for indoor lighting also mention the importance of luminance. Therefore, the design method for arranging and configuring lighting by analyzing the luminance distribution and glare reduction of the indoor space is increasing [15].

Variables that determine luminance are very diverse. In order for humans to identify an object, light reflected or emitted from the object is required. Also, as the amount of light reflected from the same object changes, humans may perceive the object differently. Therefore, the user can perceive the created light environment differently according to physical properties such as gloss, roughness, and color of the object. In addition, even if the light source is set at the same level, it can change depending on various variables such as the roughness of the illuminated surface, the viewing angle, and the position of a person. Therefore, to use luminance to evaluate a lighting environment, it is necessary to apply other variables affecting glare [16].

2.2. Typical Assessment Methods of Indoor Lighitng Environment

2.2.1. Solar Radiation

There is no indoor light environment evaluation item related to solar radiation in architecture-related certification systems of Korea (or of other countries). It is simply written as background data [17]. In the case of Leadership in Energy and Environmental Design (LEED), the average solar radiation is specified as one of the background data for evaluating the illuminance environment in the 'Daylight and Views' item of version 2.1 and 2.2 [18]. In addition, in the details of 'adaptation to climate change' among the UK Building Research Establishment Environmental Assessment Method (BREEAM) certification items, solar radiation was mentioned as an external risk factor for structural resilience evaluation [19]. As a result of the investigation, although there are some cases in which the amount of insolation is recorded to establish background data, there is no case of a certification system that directly evaluates solar radiation.

2.2.2. Illuminance

As for the standard certifications stipulated in Korea concerning illuminance, results of our investigation have shown that there are 14 standards suggested by Korean Standard (KS). Among them, 'KS C 7612-Illuminance measurements for lighting installations' and 'KS A 3011–Recommended Levels of Illumination' are being operated as certification standards that can directly evaluate an indoor illuminance environment [20,21].

KS C 7612 standard certification specifies the measurement method and conditions for indoor illuminance. Specifically, it is stipulated to measure the illuminance within 40 cm of the floor reference height or 5 cm of the working surface height. Illuminance measuring work must perform at four or more points. It is specified that the average value of the illuminance measured at four places is calculated and compared with the standard [20]. KS A 3011 provides illuminance standards according to the use of buildings and spaces. Types of illuminance measurement methods are classified according to types of spaces and activities [21]. The criteria of KS A 3011 are shown in Table 1.

In LEED, indoor illuminance is evaluated as 'LEED BD+C v4.1 Daylight' index. The method is divided into options 1 and 2 (assessed by using simulation technique) and option 3 that directly measures a space's illuminance. Option 1 is a method that simulates and calculates Spatial Daylight Autonomy and Annual Sunlight Exposure (sDA & ASE) of an indoor space. The evaluation is performed by calculating the average spatial daylight autonomy value through simulation. Option 2's method uses simulation to calculate the floor illuminance at 9:00 am and 3:00 pm based on the vernal equinox and compares it with the standard. Option 3's method directly measures and evaluates the illuminance of an indoor space to be evaluated according to the suggested measurement method [22].

Table 1. Part of the KS A 3011 standard criteria.

Types	Rank	Range (lx)	Type of Lighting
Workplaces that require a dark atmosphere	A	3–6	Overall Lighting
Low-occupancy places with dark atmosphere	B	6–15	
Dark public places	C	15–30	
Simple Workshop	D	30–60	
Workplaces that do not require eye concentration	E	60–150	
Workspace that requires high illuminance for large objects	F	150–300	Work Space Lighting
Workspace that requires high illuminance for small objects	G	300–600	
Workspace that requires high illuminance for tiny objects	H	600–1500	
Workspace that requires high illuminance for tiny objects with long time	I	1500–3000	Overall & Spot Work Space Lighting
A workspace where you need to focus on your eyes for a long time	J	3000–6000	
Very special workspace	K	6000–15,000	

2.2.3. Luminance

Regarding luminance, there are no legal or institutional standards related to architecture in Korea or other countries. However, there is an assessment index that can estimate whether a human has visual discomfort in a specific light environment. Various concepts such as unified glare rating (UGR), daylight glare index (DGI), and daylight glare probability (DGP) exist as luminance-related evaluation indicators provided by comfortable low energy architecture.

UGR is a standard formula for evaluating glare by the International Lighting Commission. It can assess the level of glare most accurately since it reflects the object that causes glare in the assessment. However, in order to calculate the estimation index, it is necessary to input various parameters such as physical properties of the object, circumstances of the surrounding environment, and angle/position with respect to the light source. Thus, it is difficult to calculate UGR accurately [23].

DGI evaluates glare caused by large light sources such as sunlight. As with UGR, DGI also calculates the glare probability differently depending on the angle between the light source, the object, and the user [24].

DGP is used with DGI as an index indicating the probability that humans will feel uncomfortable due to glare. Since DGP is calculated based on vertical surface illuminance, the human view is classified as a key parameter. The calculated DGP can be assessed based on the comfort standard suggested by Jan Wienold [25]. When the calculated value is less than 0.35, it is understood that glare does not occur [25]. The criteria of DGI and DGP are shown in Table 2.

Table 2. Comfort criteria of DGP and DGI (Adapted from Ref. [26]).

Index	Human Sense	Range	Index	Human Sense	Range	Human Sense	Range
DGP	Imperceptible	0.35 > A	DGI	Just Perceptible	16 > A	Just Uncomfortable	24 > A ≧ 22
	Perceptible	0.4 > A ≧ 0.35		Noticeable	18 > A ≧ 16	Uncomfortable	26 > A ≧ 24
	Disturbing	0.45 > A ≧ 0.4		Just Acceptable	20 > A ≧ 18	Just Intolerable	28 > A ≧ 26
	Intolerable	A ≧ 0.45		Acceptable	22 > A ≧ 20	Intolerable	A ≧ 28

2.3. Trend of Microalgae Facade-Related Studies and Differentiation of Research

The microalgae facade has a short history of research compared to eco-friendly strategies for buildings that have been actively researched (such as solar power and solar thermal energy). Therefore, research related to microalgae facade is still at a basic level. Studies of application dimensions such as understanding the unique advantages and prospects of facade systems and conditions for application to buildings are mainly conducted. Maryam Talaei has presented environmental and compositional parameters that must be considered for the construction of a new facade system through the combination of a photobioreactor and a building facade [27]. He analyzed the unique advantages and functions of the microalgae facade system, the change in a thermal environment, shading, and energy production according to the installation of the facade system from various angles. A new facade system was compared with the double skin facade system for searching parameters of microalgae facades. As a result of his research, he argued that local climatic conditions, heat production capacity, light blocking properties, and convenience of the indoor environment should be considered together for the application and construction of a microalgae facade.

In relation to an environmental analysis of a microalgae facade, Simonetta L. Pagliolico's studies have presented a microalgae envelope as a light blocking system that can control illuminance and glare [28,29]. In these studies, microalgae culture was actually performed to confirm the change in light transmittance according to the culture of microalgae. In the process, both the growth rate and light transmittance of microalgae were recorded and the data were applied to shell properties of Daysim, a mining performance simulation program. Based on the Daysim analysis conditions set through this process, mining simulations in Turin, Palermo, Italy were performed to validate the microalgae facade system. As a result, the facade system was traditional Venetian for the south, west, and north directions. It was concluded that it had a light blocking performance similar to blinds. In addition, these studies presented simulation results that the probability of occurrence of glare was higher. It was concluded that the control of the microalgae envelope could be performed in two ways based on illuminance and DGP [28].

In the next research of Simonetta L. Pagliolico, monitoring was performed for the indoor space to confirm the actual daylight blocking performance of the microalgae facade [29]. The microalgae envelope facade used for monitoring was fabricated in the form of a convex lens to reduce glare. The monitoring site was installed at Saint Marcel Kindergarten in Aosta, northwestern Italy, and the experiment was conducted for three weeks. As a result, the daylighting performance of the classroom to which the microalgae system was applied was in compliance with the legal standard, although it was close to the threshold. In addition, through the change of the facade shape, the weakness of the glare aspect presented in the previous study was supplemented [29]. Such prior studies have value as they provide data that can be used to improve the performance effectiveness in terms of indoor illuminance and glare control of the microalgal shell.

The present research has the same characteristics as Pagliolico's study in terms of the light environment. However, the microalgae facade presented in the above studies makes it difficult to be used as general building parts in the conventional architecture market. Therefore, those studies have a limitation in that they could not present universal data as a reference for performing advanced research on a photobioreactor facade in the future. In addition, previous studies in the envelope construction stage are difficult to provide a clear answer on the proportion of the microalgae envelope in total daylighting surface. From this point of view, the present research can identify changes in the environment that occur when all daylighting surfaces of a space are replaced with microalgae facades. In addition, the shape of the photobioreactor used in the experiment was designed to be similar to that of a window with a flat plate structure. Thus, the results of the present study can serve as basic data for conducting detailed studies such as construction of photobioreactor window in the future. This aspect can be said to be the differentiation point between the present study and previous studies.

2.4. Assessment Factors and Methods of Indoor Lighting Environment

In order to analyze the lighting environment of an indoor space, a literature review was conducted on environmental factors related to sunlight and evaluation methods of deduced factors. As a result, illuminance and luminance were derived as environmental factors that could determine an indoor lighting environment. As a result of examining the evaluation methods of the two derived environmental indicators, it was determined that comparative analysis through a mock-up test was possible since the criteria for each space were specified. Accordingly, in the final mock-up test, the study was conducted in the direction of exploring the type of space where the microalgae facade could be installed by measuring the VLT and indoor illuminance of a specimen.

3. Planning & Measuring Microalgae Façade Mock-Up Test

3.1. Outline of Mock-Up Test

As a microalgae culture progresses, the concentration of biomass and the turbidity increase. Accordingly, the light-transmitting property of the photobioreactor gradually decreases, making it difficult to transmit light. As a result, the microalgae facade gradually loses light transmittance and the influx of daylighting into room is reduced. Although this phenomenon itself can be understood through simple observation of the culture medium, numerical approaches to quantify natural lighting performance including window performance factors have never been attempted.

Therefore, in this study, a microalgae facade mock-up test was performed, microalgae were cultivated, and changes in the data of windows and indoor light environment were collected and analyzed during the operation period. The purpose of this test was to examine the indoor influence of a light environment of a microalgae facade. In addition, by using the collected data, we could identify the types of spaces to which the microalgae facade could be applied and explore complementary points to increase the usability of a microalgae facade.

As shown in Figure 2, a mock-up test was conducted in the order of microalgae culture specimen and mock-up planning, selection of microalgae species, window performance of specimen according to microalgae culture and light environment measurement of the mock-up inside. For the microalgae species used in the test, *Chlorella vulgaris* was selected. *Chlorella vulgaris* is a nationally approved culture method for producing biomass [30]. For the microalgae test specimen, a chamber-type specimen was manufactured by applying specifications of microalgae windows registered in the Korean Intellectual Property Office [31]. At the same time, the indoor space of the mock-up produced a box-type structure that could install and operate the test body. During the cultivation process, VLT was measured for each unit time and illuminance data were collected to analyze the indoor light environment.

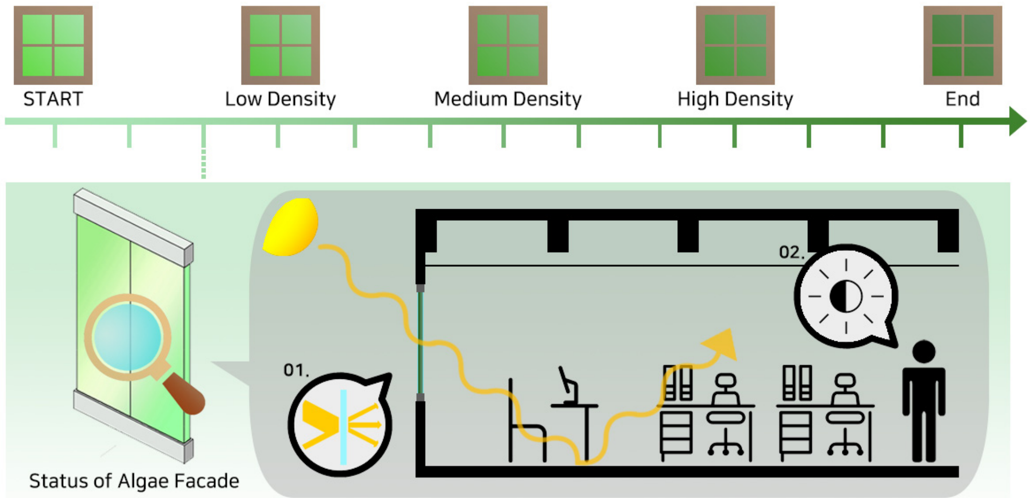

Figure 2. Mock-up test method (Adapted from Ref. [26]).

3.2. Scope and Variables of Mock-Up Test

The temporal range of the mock-up test was set based on the culturing temperature of *Chlorella vulgaris* presented in the book 'Freshwater Green Algae Cultivation Methods and Agricultural Use' provided by the National Academy of Agricultural Sciences. According to the above guideline, the optimum culture temperature for *Chlorella vulgaris* microalgae suggested is 28–30 °C and the maximum culture temperature range is 15–40 °C [30]. There is a possibility that the culture rate will be slow without separate equipment such as hot water or warm air supply in winter when the outdoor temperature can be decreased to 15 °C or less. For the purpose of the experiment, it is necessary to identify changes over time, and the outdoor temperature must be a control variable.

In addition, among conditions of the mock-up test, factors that can change the light environment over time are mainly altitude and position of the sun. As a result of analyzing the difference in height and position of the sun in spring, summer, and autumn (using the sunpath diagram according to these conditions), it was found that there was no difference in the sun position between spring and autumn. Therefore, the time range of the mock-up test was reduced by considering spring and autumn time points as the inter-season.

Finally, the winter in which culture conditions were not established was excluded from the time range of the test. Spring and winter seasons were integrated due to similarly concept of inter-season's sun position and sunlight hours. Based on this premise, summer and autumn were selected as the temporal range of the mock-up test. Specifically, the 'summer solstice' and 'autumn equinox', showing seasonal characteristics of summer and autumn, were chosen to be the temporal criteria. The duration of the mock-up test was set to be two weeks based on the maximum culture period of *Chlorella vulgaris* suggested by the Rural Development Administration. Recording time points of lighting environment and window data were set at 09:00, 12:00, and 18:00 based on the general building operation schedule in Korea.

The spatial extent of the mock-up test must pick a place without shield around it in order to control the influence of external shielding elements. In addition, the culture of microalgae should be in a place that is difficult to access by people not involved in the test and easy to maintain continuously. According to these conditions, the test site was conducted on the roof of Engineering Building No. 2 in Chonnam National University.

As the equipment used in the test, WP-4500 Window Energy Profiler was used among Window Profilers that could measure the performance of light-transmitting materials including glass as shown in Table 3. For indoor lighting environment measurement, TM-208, which could measure solar radiation, illuminance, and ultraviolet rays, was used. The conditions required for culturing microalgae were planned based on the national technical data used for time range selection. Finally, the culturing was carried out for two weeks at a stage in which the microalgae's density was 10% [30]. To minimize the influence of climate, the most important control variable for the test, climatic conditions were recorded by taking pictures of the surrounding area and sky at each time point of measurement of window performance and light environment.

Table 3. Equipment used for the mock-up test.

Photo	Name	Measuring Parameters	Photo	Name	Measuring Parameters
	WP-4500	VLT, SHGC, Infrared, Ultra Violet		TM-208	Ultra Violet Light, Solar Radiation, Illuminance

3.3. Construction of Speciman and Mock-Up

As shown in Figure 3, the size of the mock-up was 1500 mm in width, 1400 mm in length, and 1600 mm in height. It had a box shape (close to a cube shape). This box-shaped structure was divided into a specimen installation space and an indoor space. The front-side could install a panel with a square-shaped of 1200 mm in length. The back-side was an empty space where measuring equipment could be installed to judge the effect of indoor space. The two spaces were separated by a 3 mm single plate glass and a 30 mm thick polyvinyl chloride (PVC) window frame. The composition of the mock-up was designed to utilize the measurement method of 'KS C 7612-Illuminance measurements for lighting installations'. Accordingly, the indoor space of the mock-up was configured with a height of up to 1200 mm to perform both floor and working surface's brightness measurements. It was possible to install an 800 mm height object, the working surface height suggested in KS C 7612. A mock-up was constructed according to these conditions to overcome the difference in scale between building and mock-up, which was a limit of the experiment, and to secure the significance of experimental data.

The mock-up was divided into specimen's installation space and indoor space. The material of the mock-up was a stainless-steel square frame with a sandwich panel. The interior was divided into areas by installing a 3 mm single-layer glass window at a position 100 mm away from the front to the inside to distinguish the test specimen installation space from the indoor space.

For comparison of the specimen with 3 mm single glass performance and the specimen cultured with microalgae in the same environment, two specimens and mock-ups were produced each as shown in Figure 4. In the test, microalgae culture was carried out only on one specimen among the two specimens and the trend of change of each specimen was compared during the culturing process. The culture of the microalgae was carried out in mock-up 01. Mock-up 02 was not operated separately.

3.4. Progress of Mock-Up Test

In order to perform the microalgae facade mock-up test, temporal and spatial ranges, test method, test procedure, and so on were stipulated. Test data were collected from the rooftop of Chonnam National University College of Engineering Building No. 2 for about two weeks from 22 June 2020 and 22 September 2020. During the test period, microalgae culture was carried out without any setback. Window performance and indoor illuminance data were collected for each unit time according to the lapse of operating hours. Figure 5 shows the process of changing the microalgae facade during the test period.

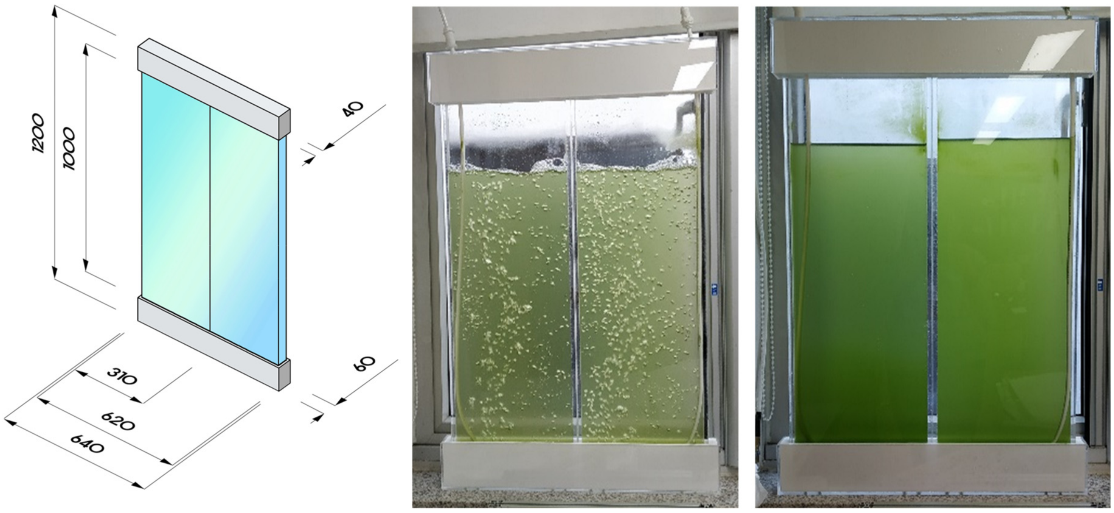

Figure 3. Test specimen of microalgae façade (Adapted from Ref. [26]).

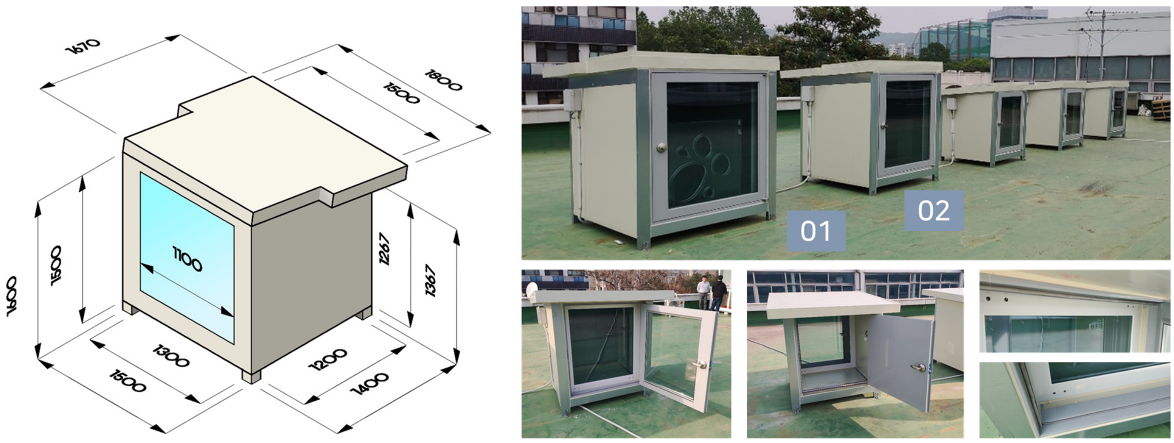

Figure 4. Construction of mock-up (Reprinted from Ref. [26]).

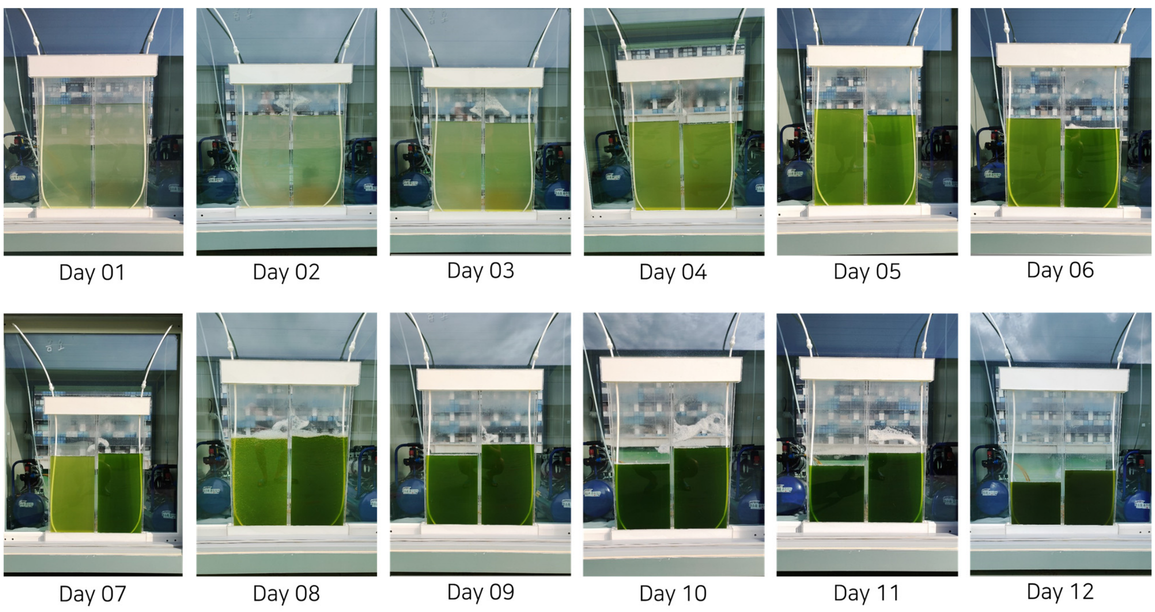

Figure 5. Change of microalgae's density during mock-up test (Adapted from Ref. [26]).

4. Analysis of Collected Window and Illuminance Data

4.1. Summer Season

As for the weather conditions at summer solstice, 8 days out of the 15-day measurement period were found to be rainy conditions. Accordingly, measured data at the summer solstice were generally recorded in 'cloudy' or 'raining' conditions. Averaged daily temperature was in the range of 20–30 °C and wind speed was 1.0–3.2 m/s. The amount of cloud cover did not fall below 40% depending on characteristics of summer season. Whole climate data are presented in Figure 6.

In summer, the wind speed and total cloud cover increased depending on whether it was rainy. However, the temperature and solar radiation decreased. These climate change characteristics could be classified as climatic conditions corresponding to the rainy season among general summer characteristics of Korea. The rainfall period was longer than in autumn. In addition, the ratio of total cloud cover did not fall below 40% even at the time of monitoring when there was no rain, confirming the characteristic that a certain level of cloud was continuously present in the sky during the monitoring period.

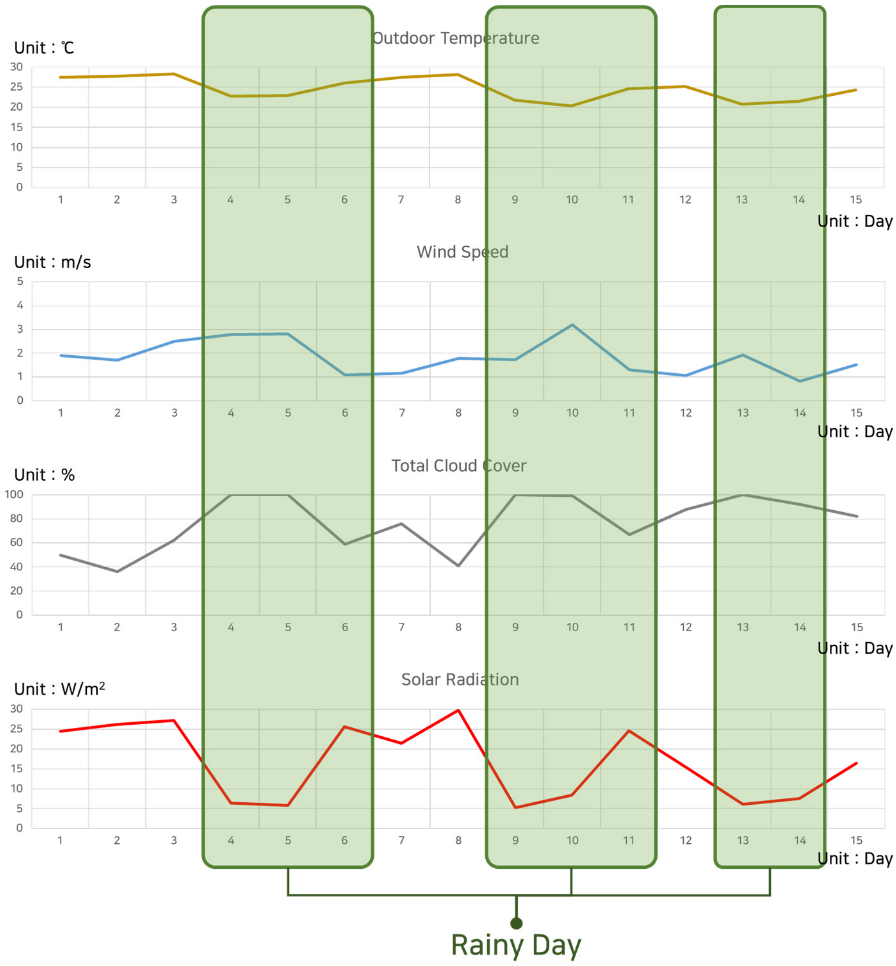

Figure 6. Weather conditions in summer season.

The VLT of microalgae specimen was recorded as 25% in first measurement time of mock-up 01. The VLT for each measurement time of DAY 01 hardly changed. However, from 6 pm on DAY 03, the window performance dropped to single digits and decreased to 9% as shown in Figure 7. From DAY 04 to DAY 08 thereafter, the test specimen's performance showed a continuous decreasing trend. The value of VLT dropped to 1%. Afterwards, the measured value was maintained at 1% level from DAY 09 to DAY 15. Thus, the range of VLT Change at summer solstice fell from 25% to 1% over a week. The averaged

VLT value during whole culturing period was 6%. In contrast, averaged VLT of mock-up 02 was 85%, revealing a 14-fold difference in performance.

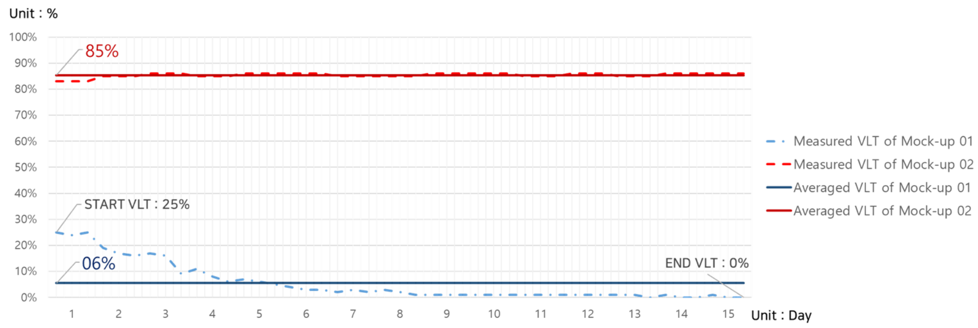

Figure 7. VLT change of mock-up 01 and 02 in summer season.

As shown in Figure 8, the initial measured illuminance at the floor of mock-up 01 was 6780 lx, indicating that an illuminance environment of about 54.0% was created compared to the illuminance value of 12,550 lx measured in mock-up 02. When the average illuminance for each measurement time was compared, average illuminance values at 9 am of mock-up 01 and 02 were measured to be 1612.45 lx and 4017.17 lx, respectively. The indoor environment of the microalgae facade was 40.1% compared to the normal glass performance. The trend became stronger as it approached noon. Measured illuminance values of mock-up 01 and 02 were 1624.48 lx and 4548.33 lx, respectively. Mock-up 01 created an illuminance environment of 35.7%. Finally, even at 6 pm, the measured value was 322.07 lx for mock-up 01 and as 941.86 lx for mock-up 02. As a result of comparing the indoor illuminance of the two mock-up specimens, mock-up 01 showed that it was possible to create an illuminance environment at a level of 34.1% compared to mock-up 02.

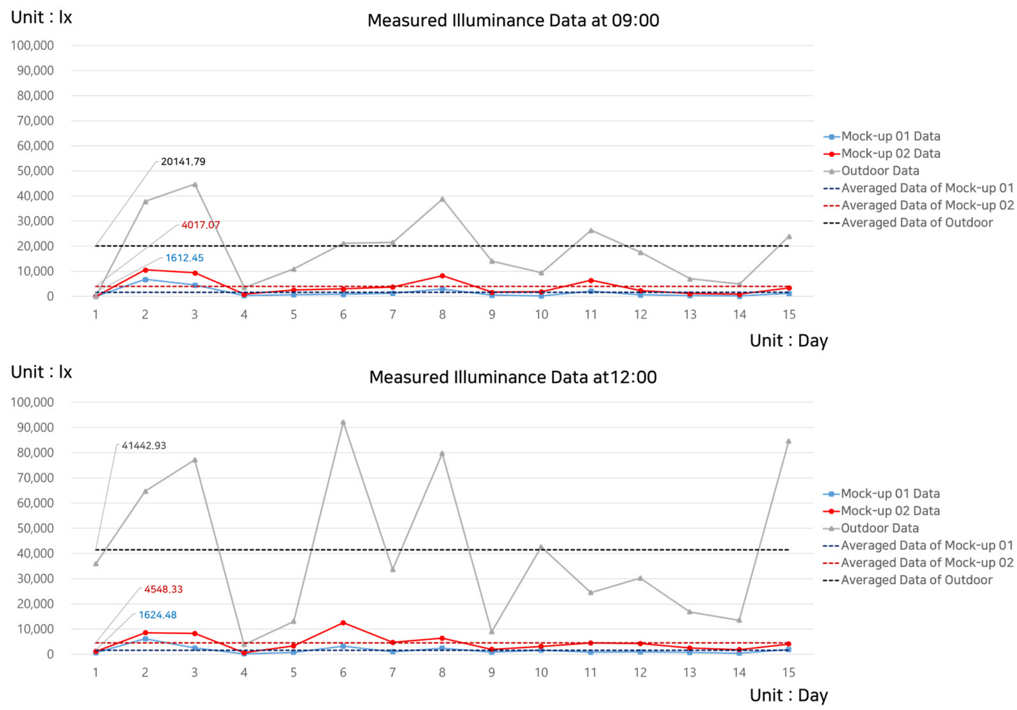

Figure 8. *Cont.*

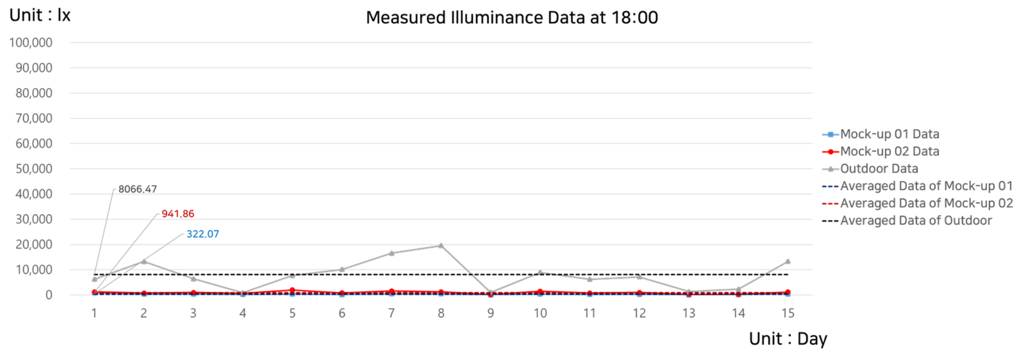

Figure 8. Measured illuminance data in summer season.

4.2. Autumn Season

Weather conditions at the time of the autumn equinox were rainy for 4 days out of the 15-day measurement period. The rain was mainly concentrated in the first half of the measurement period. After that, during the mid-to-late period of the trial, no cloudy days occurred except for DAY 09. In this situation, the time of the autumn equinox was generally recognized under conditions of 'less clouds' or 'clear sky'. The average daily temperature was 20–25 °C and wind speed was at 1.0–2.2 m/s. The average amount of total cloud cover was 0–40% except for rainy weather and DAY 09. Accordingly, the test was progressed in a situation in which cloudy and clear sky were mixed. Whole climate data are presented in Figure 9.

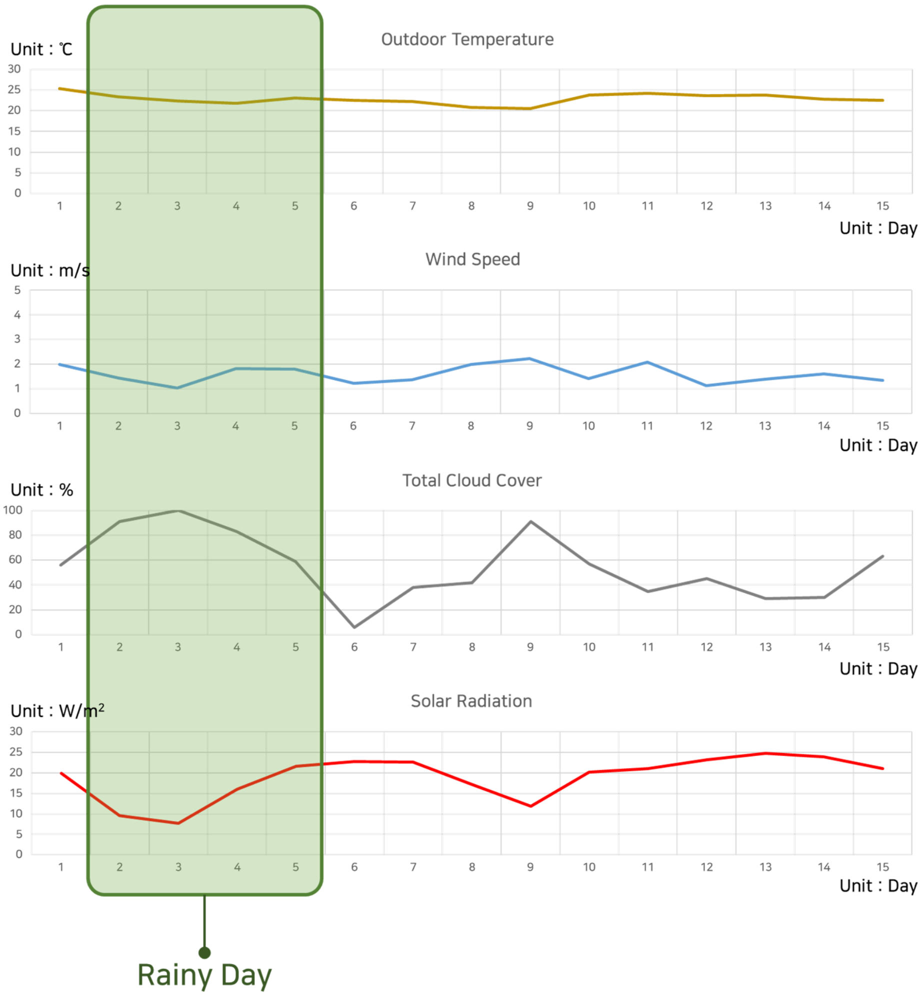

Figure 9. Weather conditions in autumn season.

In the case of autumn, it rained from Day 02 to Day 05. In the latter half of the monitoring period except for Day 09, the total cloud coverage stayed at 30–50% overall, unlike in the summer time. As a result, the solar insolation also showed a high inflow of more than 20 W/m^2 of insolation per hour on average per day except for Day 09. Through this, it appears that the weather characteristics of autumn are higher and sunny than summer and that atmospheric conditions hindering solar inflow are less in autumn than in summer.

The VLT measured at mock-up 01 at the time of the autumn equinox was 29%. The VLT showed a rapidly tendency to decrease over DAY 01 to DAY 03 as shown in Figure 10. After that, it showed a gentle decreasing trend again until DAY 06. The fluctuation of the VLT measurement value slowed down at a level of 10%. However, during the period from DAY 07 to DAY 09, the trend of change in VLT accelerated again and decreased to the lowest value of 1%. Mock-up 01's window performance remained at a level of 1% during the period from DAY 10 to DAY 15. The VLT variation range at the time of the autumn equinox was 1–29%, which was similar to that of the lower extremities. Average VLT was 9%, which was 3% higher than the lower extremities. It resulted in a performance difference of 9.6 times compared to the average VLT measurement value of mock-up 02.

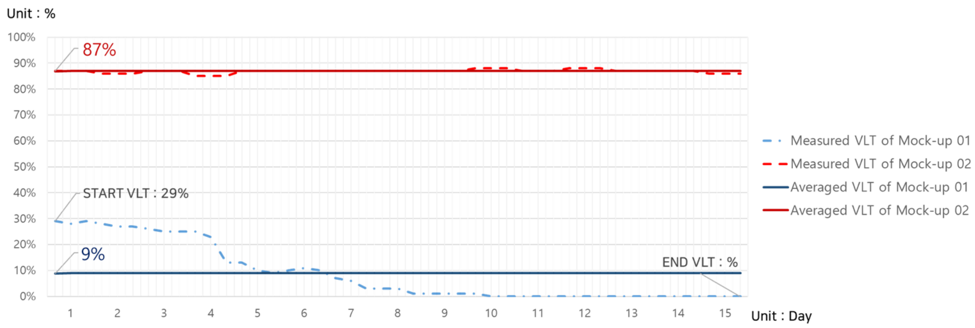

Figure 10. VLT changes of mock-up 01 and 02 in autumn season.

As presented in Figure 11, the maximum illuminance during the autumn equinox monitoring period of mock-up 01 was 6400 lx, which recorded 22.6% of the indoor illuminance level compared to the 28,290 lx shown in mock-up 02 without the microalgae culture. At 9 am, the measured illuminance of mock-up 01 was 3162.20 lx, which was 27.1% of the 11,639.73 lx of mock-up 02. Measured values of mock-up 01 and mock-up 02 at noon were 3339.67 lx and 1441.47 lx, respectively. It was found to be at a level of 23.1%. Finally, the indoor illumination environment for mock-up at 6 pm had 84.56 lx and 265.14 lx for mock-up 01 and 02, respectively, which was only 31.8%.

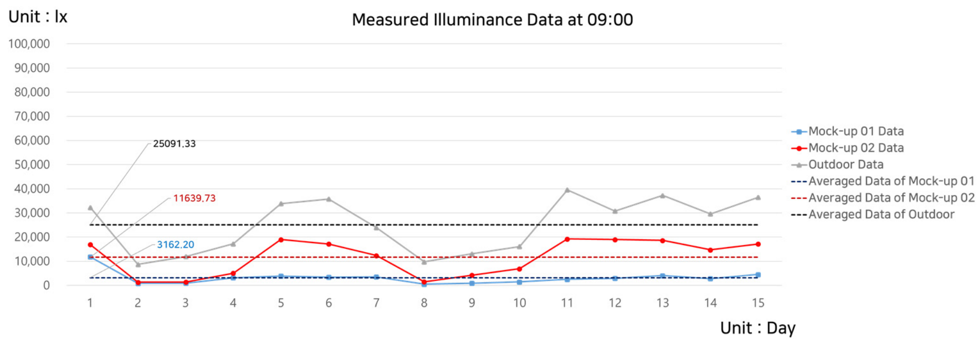

Figure 11. *Cont.*

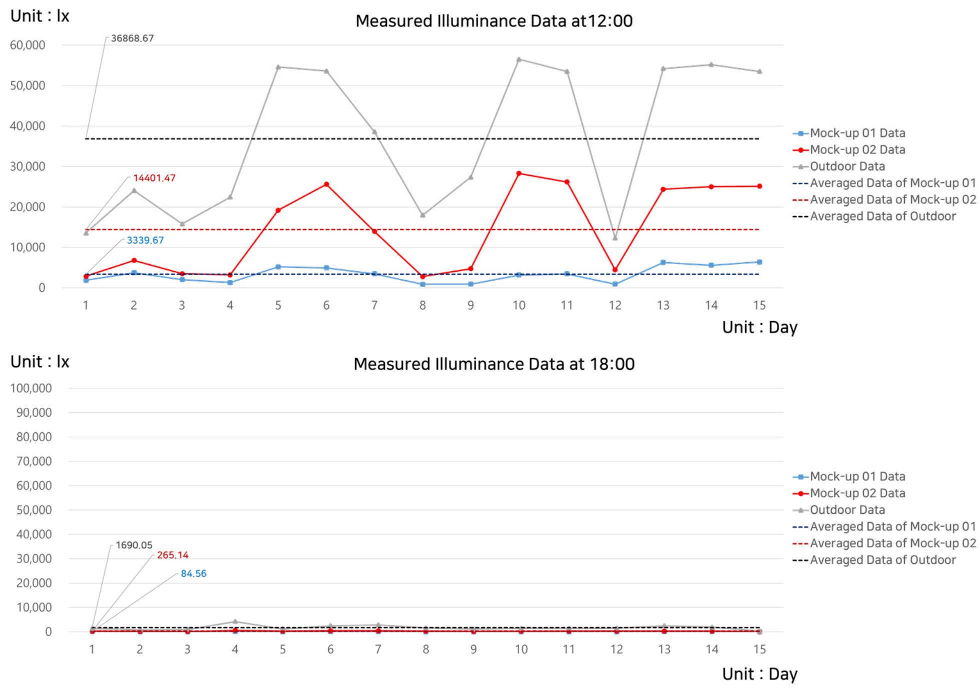

Figure 11. Measured illuminance data in autumn season.

4.3. Analysis Results

By conducting window performance and indoor illuminance measurement tests at the summer solstice and autumn equinox, the composition level of the indoor light environment according to the application of the microalgae facade was identified. As a result, the indoor illuminance of mock-up 01 at the summer solstice was found to be from 34.1 to 40.1% of that of mock-up 02. The measured illuminance of mock-up 01 was decreased to a maximum of 39.37 lx. When these results were compared with the standards specified in KS A 3011, it was found that the indoor illuminance of mock-up 01 could fall to the level of a 'space where simple work for a short time'.

The trend was stronger at the time of the autumn equinox. Average VLT and indoor illuminance of mock-up 01 during the period were 22.6–27.1% of the indoor illuminance level compared to the mock-up 02 environment. Accordingly, the minimum illuminance of mock-up 01 was dropped to 38.68 lx. When substituting the KS A 3011 illuminance standard, the light environment of mock-up 01 may fall to the same level as the summer season.

Through these test data, it was found that the microalgae window could drop to a maximum of 38–39 lx level regardless of the change in climatic conditions as the operating time elapsed under an environment wherein microalgae windows could be cultured and operated.

Spaces suitable for the minimum illuminance environment of the microalgae facade installation space classified in KS A 3011 include 'race track, stadium audience seats', 'emergency stairs', 'garage', and 'warehouse'. These types are classified as spaces that do not require natural light. At the same time, it was found that the work environment illuminance standard did not satisfy the minimum standard illuminance of 60 lx for performing 'rough work'. Based on these results of the mock-up test, it is recognized that if the building facade only considers the microalgae window standard currently presented by Korean Intellectual Property Office, a daylighting environment will be created that is unsuitable for performing any work. Therefore, it is judged that it is necessary to supplement microalgae window specifications and change the compositions of microalgae facades in order to construct a bio-facade that can simultaneously meet the energy production function and the existing daylighting performance.

In particular, it is expected that an area through which sunlight can be transmitted and a space with culture function must be mixed by changing the configuration, such that

100% of the light transmitting area suggested in the existing microalgae window standard can be used as a culture chamber. In the existing microalgae culture space, 100% of the permeable surface of the window was used as the culture area due to the efficiency of culturing. However, in this case, it is necessary to change the pipe system suggested in the existing standard. Accordingly, a redesign process is required. On the other hand, as a method of increasing the permeability of the microalgae window in terms of configuration, a method of constructing a permeation area in the existing culture chamber can also be suggested. The method may create a space that cannot be filled with water in a rectangular culture chamber and configure the area as a light transmitting surface. It can be seen as a method that can accommodate changes in the skin according to the design thinking of architects more flexibly, ultimately securing both aesthetic value and eco-friendly value.

In addition, depending on the location of the sunlight-transmitting surface in the culture space, the type of spaces to which the microalgae facade can be applied may be diversified. For example, if the position of the sunlight-transmitting surface is the same as the test specimen used in this study, the intact light-transmitting surface will be the upper part of the window. It can act as a skylight. The configuration method can be used in a private space that prevents the view from the outside. Conversely, when the light-transmitting surface is located in the middle of the culture space, it is possible to protect the user's right to view even though it cannot play the role of a skylight. In this way, by composing the complete light-transmitting surface in various ways in terms of composition, the designer's thoughts and intentions and user convenience can be considered together, which can be sublimated into another architectural expression technique.

5. Conclusions

Microalgae are new bioenergy resources that have been attracting attention as resources with high eco-friendliness compared to existing energy production methods. However, current microalgae research remains at a basic level. Installation and operation of the actual building and review of problems associated with it have not been performed. Since a Photovoltaic Panel has been commercialized through repeated research, the microalgae facade also needs to be constructed as a practical energy production method by conducting basic research in the present.

From this point of view, in this study, mock-up tests were performed to understand the architectural applicability of a microalgae facades from the perspective of the lighting environment. Window and indoor illuminance performance of the microalgae facade were comparatively analyzed. As a result, it was confirmed that it was necessary to revise the standard of existing microalgae windows and to reduce the turbidity by reducing the thickness of the culture space to increase the VLT and indoor illuminance performance. In addition, this research checked daylighting performance of building facade in which the specific gravity of the photobioreactor was 100%. It is also important to control variables in design aspect. Results of this study can be used as background data for microalgae facade related research insofar that this study confirms that environmental change occurs in the indoor space when all facade surfaces are composed of the photobioreactor. Accordingly, this study is meaningful in that it presents specific data on the change and effect of the daylighting environment when a microalgae facade is applied to a unit space that conforms to the Korean national standard.

However, the limitation of this study is that a mock-up test has a fundamental difference in scale from an actual building, even if the problem of scale is recognized and supplemented. If the area of the microalgae facade is increased to a size larger than the standard suggested in the research, the results of this study may be different from other experimental results. In addition, this study was conducted based on the specification of the Korean Intellectual Property Office which lacked representativeness, considering the limitations of climate condition control and the fact that the concept of the microalgae facade has not yet been established. Therefore, the next research on the influence of the indoor environment according to the change in the size and composition of the microalgae window should be conducted from various viewpoints to determine the composition of a microalgae facade suitable for use in buildings. Based on the results of research to be carried out in the next stage, the types and specifications of microalgae facades that can create a suitable environment according to the use of buildings in terms of laws and institutions should be suggested.

In addition, another limitation of the research is that the effect of microalgae facades was handled only from the view of daylighting environment (although the basic purpose of those is to produce biomass). Therefore, the cultivation settings of microalgae can recognize as one of critical factors that cannot be overlooked in the construction of the envelope. If the energy required for culturing is higher than the total amount of its production, microalgae facade may lose its inherent advantages. So, they should be implemented in an integrative manner in terms of building energy balance and thermal condition in addition to the indoor environment. In this regard, Pruvoset's study showed that composition and operation methods of the vertical microalgae facade could be changed for the construction and maintenance of the photobioreactor facade through the comparison of thermal balance between the existing skins with vertical space and the building [32]. The results of the above research can be viewed as another basis for arguing that the structural aspect of the existing microalgae facade needs to be changed. Therefore, in future studies, various conditions for functional performance and optimization of microalgae facades such as the daylighting environment, building energy balance, and thermal environment are to be considered in a converged way and presented as a new configuration method.

Author Contributions: S.-J.C. and S.-H.H. designed the research settings; S.-J.C. performed the evaluations; S.-J.C. and S.-H.H. analyzed the data; S.-H.H. verified the analysis results; S.-J.C. and S.-H.H. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and ICT of the Korean Government (Project No.: NRF-2021R1A2C2011893).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was developed from a graduate thesis by Seung-Ju Choe and supported by a grant from the Basic Science Research Program through the National Research Foundation of Korea (Development of Smart Building Envelopes towards Implementation of Vernacular Energyscape).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Oh, Y. Current status and prospect of biofuel production using microalgae. *Korean Soc. Environ. Agric.* **2012**, *2012*, 3–24.
2. Henrikson, R.; Edwards, M. *Imagine Our Algae Future: Visionary Algae Architecture and Landscape Designs*; CreateSpace Independent Publishing Platform: Scotts Valley, CA, USA, 2012; pp. 3–37.
3. International Energy Agency. World Energy Outlook 2014. Available online: https://www.iea.org/reports/world-energy-outlook-2014 (accessed on 24 April 2020).
4. Renewable Energy Magazine. IBA Hamburg Opens the First Algae Biomass Building. Available online: https://www.renewableenergymagazine.com/biomass/iba-hamburg-opens-the-first-algae-biomass-20130514 (accessed on 24 April 2020).
5. Algae Curtain. Available online: https://www.photosynthetica.co.uk/cladding (accessed on 24 April 2020).
6. The European Portal for Energy Efficiency in Buildings. Available online: https://www.buildup.eu/en/practices/cases/biq-house-first-algae-powered-building-world (accessed on 24 April 2020).
7. Seyrek, C.I.; Widera, B.; Woźniczka, A. Sustainability-Related Parameters and Decision Support Tools for Kinetic Green Façades. *Sustainability* **2021**, *13*, 10313. [CrossRef]
8. Santi, G.; Bertolazzi, A.; Leporelli, E.; Turrini, U.; Croatto, G. Green Systems Integrated to the Building Envelope: Strategies and Technical Solution for the Italian Case. *Sustainability* **2020**, *12*, 4615. [CrossRef]
9. Lee, J. A Study on the Assessment of Architectural Aspects of School Classrooms: Focused on Sunshine, Insolation, Illumination. Master's Thesis, University of Changwon, Changwon, Korea, 2007.
10. Kim, T. Estimation of Solar Insolation Based on Himawary Satellite Data with CNN. Master's Thesis, University of Seoul, Seoul, Korea, 2019.

11. Kempton, L.; Kokogiannakis, G.; Cooper, P. Mould risk evaluations in residential buildings via site audits and longitudinal monitoring. *Build. Environ.* **2021**, *191*, 107584. [CrossRef]
12. Park, Y.; Park, J. A study of Energy Use Impacts by SHGCs of Windows in Detached House. *Korean J. Air-Cond. Refrig. Eng.* **2010**, *22*, 189–196.
13. Industrial Safety Dictionary. Available online: https://terms.naver.com/entry.naver?docId=508750&cid=42380&categoryId=42380 (accessed on 24 April 2020).
14. Kim, I.; Kim, S.; Hong, W. A Study on the Proper Illuminance Considering the Task Amenity of the Occupant in the Office Space. *J. Archit. Inst. Korea Struct. Constr.* **2020**, *36*, 159–167.
15. Lee, J.; Kim, W. Analysis of Impacts of Luminance of Luminous Source and Luminous Area on GSV. *J. Archit. Inst. Korea* **2007**, *23*, 295–302.
16. Jeong, U. Visual Environment Assessment of Office Space Daylighted by Transparent BIPV Window System. Master's Thesis, University of Hanbat, Daejeon, Korea, 2013.
17. Building Energy Efficiency Rating Certification System. Available online: https://beec.energy.or.kr/BC/BC02/BC02_02_001.do (accessed on 27 April 2020).
18. Leadership in Energy and Environmental Design. LEED 2.0 Daylight and Views. Available online: https://www.usgbc.org/credits/new-construction/v20/eqc81?view=interpretations (accessed on 27 April 2020).
19. Qtaishat, Y.; Adeyeye, K.; Emmitt, S. Eco-Cultural Design Assessment Framework and Tool for Sustainable Housing Schemes. *Urban Sci.* **2020**, *4*, 65. [CrossRef]
20. Korean Agency for Technology and Standards. KS C 7612 Illuminance Measurements for Lighting Installations. Available online: https://standard.go.kr/KSCI/standardIntro/getStandardSearchView.do (accessed on 27 April 2020).
21. Korean Agency for Technology and Standards. KS A 3011 Recommended Levels of Illumination. Available online: https://standard.go.kr/KSCI/standardIntro/getStandardSearchView.do?ksNo=KSA3011&menuId=919&reformNo=09&tmprKsNo=KSA3011&topMenuId=502&upperMenuId=503 (accessed on 27 April 2020).
22. Leadership in Energy and Environmental Design. LEED v4 for Building Design and Construction. 2019. Available online: https://www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version (accessed on 27 April 2020).
23. International Commission on Illumination. Discomfort Glare in Interior Lighting. Available online: https://cie.co.at/publications/discomfort-glare-interior-lighting (accessed on 27 April 2020).
24. Yun, K.; Cho, S.; Kim, K. Daylighting Performance Evaluation based on Visual Environment Criteria in an Office Space. *J. KIAEBS* **2011**, *2011*, 230–233.
25. Konstantzos, I. Daylight Glare Probability Measurements and Correlation with Indoor Illuminances in a Full-Scale Office with Dynamic Shading Controls. In Proceedings of the 3rd International High Performance Buildings Conference, West Lafayette, IN, USA, 14–17 July 2014; Paper 147. Available online: https://docs.lib.purdue.edu/ihpbc/147 (accessed on 27 April 2020).
26. Choe, S.-J. A Study on the Spatial Applicability for Buildings by Analyzing Daylight Performance of Microalgae Windows. Master's Thesis, Chonnam National University, Gwangju, Korea, 2021.
27. Talaei, M.; Mahdavinejad, M.; Azari, R. Thermal and energy performance of algae bioreactive façades: A review. *J. Build. Eng.* **2020**, *28*, 101011. [CrossRef]
28. Pagliolico, S.L.; Verso, V.R.L.; Bosco, F.; Mollea, C.; La Forgia, C. Novel Photo-bioreactor Application for Microalgae Production as a Shading System in Buildings. *Energy Procedia* **2017**, *111*, 151–160. [CrossRef]
29. Pagliolico, S.L.; Verso, V.R.L.; Zublena, M.; Giovannini, L. Preliminary results on a novel photo-bio-screen as a shading system in a kindergarten: Visible transmittance, visual comfort and energy demand for lighting. *Sol. Energy* **2019**, *185*, 41–58. [CrossRef]
30. Rural Development Administration National Academy of Agricultural Sciences. Chlorella [Freshwater Green Algae] Cultivation Method and Agricultural Use. Available online: http://eas.rda.go.kr/EAS/cmm/fms/FileDown.api?atchFileId=FILE_000000000041167&fileSn=0 (accessed on 3 May 2020).
31. Korean Intellectual Property Office. Windows for Cultivation of Microalgae for Bio-Energy Production. Available online: http://kpat.kipris.or.kr/kpat/biblioa.do?method=biblioFrame (accessed on 18 May 2020).
32. Pruvost, J.; Le Gouic, B.; Lepine, O.; Legrand, J.; Le Borgne, F. Microalgae Culture in Building-integrated Photobioreactors: Biomass Production Modelling and Energetic Analysis. *Chem. Eng. J.* **2016**, *284*, 850–861. [CrossRef]