Verification of the Energy Attributes of a Biochromic Facade through Real-time Measurements

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ABSTRACT: Microalgae facades can significantly impact a building's energy consumption and carbon neutrality. This particular facade achieves this effect through various mechanisms, including dynamic shading efficacy, winter solar gain, dynamic visual light transmission, carbon sequestration through photosynthesis, and the transfer of produced oxygen to indoor space. While numerous smart facades have been introduced in the contemporary era, the imperative to attain zero-carbon buildings has intensified the quest for nature based, sustainable solutions characterized by minimal carbon production and real time carbon sink throughout their life cycles. This paper aims to assess the potential for reducing building energy consumption by examining the influence of microalgae facades on Solar Heat Gain Coefficient (SHGC) and Visual Light Transmission (VLT).

The research employs a combination of experimental and simulation approaches to facilitate comprehensive result comparisons. Microalgae façade samples were prepared at four distinct cell densities (25%, 50%, 75%, and 100%) to examine the density's impact on SHGC and VLT. Furthermore, the study undertakes a comparative analysis of energy consumption of a reference building and a microalgae building across diverse climates. This comparison is conducted using conventional glazing according to ASHRAE 90.1 and microalgae facades with varying cell densities, contributing to a nuanced understanding of their respective energy efficiency implications. The results indicate that cell density and thickness of microalgae facades can play a key role in SHGC and VLT. Therefore, microalgae can act as a façade with dynamic U-value and VLT depending on different climate zones. The results indicate that almost in all climates integrating microalgae façade can reduce the energy consumption by 4% to 12%.

KEYWORDS: microalgae façade, decarbonization, energy efficiency, dynamic solar heat gain, visual light transmission.

INTRODUCTION

The existence of various crises in the field of global warming, ozone layer perforation, and the excessive increase in greenhouse gas emissions has prompted a reevaluation of various aspects across sectors (Falkowski, et al. 2000) (Pittock 2009). One crucial aspect that should be considered in every sector is energy consumption, as 80% of greenhouse gas emissions are linked to the energy sector [3]. Buildings can play a pivotal role in reducing energy consumption and environmental problems. Buildings in the United States are responsible for approximately 40% of CO2 emissions, 40% of energy consumption, and 70% of electricity use (EIA 2017) (Nejat, et al. 2015) (Saxton 2019).

Despite efforts at different levels to derive energy from renewable sources, only 20% of electricity production in the United States utilizes renewable sources, and fossil fuels still hold a significant share in electricity production (Office of Energy Efficiency & renewable Energy 2023). Therefore, finding sustainable solutions to reduce energy consumption and generate clean energy in the building sector becomes imperative.

One such solution is the use of microalgae, whose applications are expanding across different sectors due to their unique properties. Microalgae can serve as an environmentally friendly source of food, energy, and animal feed [8], providing possibilities for biofuel production (Sharma, et al. 2012) (Coppo, et al. 2014) (Shurtz, Wood and Quinn 2017).

Feasibly, a bioreactor facade within a building can be established through the integration of a microalgae facade. Such integration proves considerably more versatile and sustainable compared to conventional facades. This innovative approach not only reduces carbon dioxide emissions but also enhances indoor air quality by leveraging the oxygen produced during photosynthesis. Additionally, the flexibility to adjust the microalgae cell density based on seasonal variations and the demand for solar heat gain regulations allows dynamic control over shading levels, thereby aiding in diminishing both cooling and heating loads. Moreover, microalgae facades exhibit the capacity to generate biomass and thermal energy through harnessing sunlight and contribute to a positive influence on the building's acoustic environment (Talaei, et al. 2022) (Pagliolico, et al. 2019).

1.0 LITERATURE REVIEW

Numerous articles have explored the utilization of microalgae facades in buildings, investigating their impact on diverse metrics such as energy consumption, indoor air quality, thermal comfort, solar heat gain, and other relevant parameters. Kim (Kim 2013) investigated the impact of microalgae facades on multiple parameters, including thermal performance, daylighting, and structural aspects. This research, employing simulations and experiments, took place in North Carolina. The findings revealed a substantial positive effect, indicating an enhancement in the building's thermal and daylight performance through the incorporation of this facade type. Based on the results, the microalgae facade's U-factor is comparable to that of an insulated glass unit (IGU) with a low-e coating. Moreover, the vision zone can illuminate the perimeter zone of interior space without using any artificial lighting.

Elnokaly et al. (Elnokaly and Keeling 2016) conducted an additional study involving experimentation to investigate the impact of microalgae density and shading in Lincoln, United States. The results of this experiment revealed that an increase in microalgae density led to a decrease in light penetration and internal luminance. Furthermore, the study observed a weak correlation between culture density and shading efficiency. Sadra et al. (Sadra and Vicente 2016) in Madrid, Spain, conducted research on the effects of employing a specific microalgae profile using simulation and theoretical methods. According to the findings of this study, the microalgae facade has the potential to significantly reduce energy consumption. Araji et al. (Araji and Shahid 2018) investigated factors such as shape, panel orientation, and other relevant parameters to enhance the performance of integrated flat panels containing microalgae. A comparative analysis between aspect ratios of 1:8 and 1:1 revealed that a building with a 1:8 aspect ratio has a higher potential to achieve a net-zero energy building rather than a 1:1 ratio building by 40.31% due to energy saving potential. Additionally, the photobioreactor (PBR) with a 75° panel orientation demonstrated superior energy efficiency compared to its counterpart with a 90° orientation.

Shading devices have a positive impact on energy consumption. A study by Martokusumo et al. (Martokusumo, et al. 2017) compared temperature differences indoors and outdoors by comparing façade brise soleil, a horizontally fixed shading device, and algae PBR. They conducted this study in Indonesia using experiments and simulations. The results indicate that the PBR facade has the highest temperature difference (6.447°C) while the algae bioreactor can reduce daylight by more than 90%. The consumption of energy cooling (district cooling) for the building integrated algae PBR is less than the energy consumption of the façade applying brise soleil and horizontally fixed shading device.

The integration of biomass production with the building offers significant advantages. In a theoretical exploration and simulation conducted by Provost et al. (Pruvost, et al. 2016), the study delved into the impact of PBR inclination, light interception, and various parameters on biomass productivity and energy consumption for generating 1 ton of biomass in Nantes, France under six distinct conditions (varying based on inclination degree, thermal symbiosis efficiency, PBR thickness, and night mixing). The results indicate that the symbiotic relationship between the microalgae bioreactor and the building façade can substantially reduce the energy requirements for microalgal culture compared to standalone solar PBRs. In comparison to PBR façades lacking thermal symbiosis and those with 50% thermal symbiosis, PBR façades with 100% symbiosis yield require less energy for the annual production of one ton of biomass. Additionally, these PBR façades with 100% symbiosis yield do not undergo night mixing. Furthermore, the heat generated by the microalgae façade can be effectively utilized within interior spaces. According to a study conducted by Kerner et al. (Kerner, et al. 2019), 80% of the heat produced by the microalgae façade can be harnessed for heating purposes in interior spaces.

Despite the existing research in the field of microalgae, further investigation is needed to comprehensively study the impact of various biological and architectural variables on building energy consumption. To enhance and broaden the utilization of microalgae facades, it is imperative to assess the efficiency and performance of this architectural feature under diverse conditions by examining various parameters. These parameters encompass design aspects like form, orientation, and thickness, as well as factors related to microalgae, including species, density, and environmental conditions such as climate and test location.

2.0 MEASUREMENTS OF ENERGY ATTRIBUTES

SHGC (Solar Heat Gain Coefficient) and VLT (Visible Light Transmittance) are two important energy attributes that impact heating, cooling, and lighting loads. To estimate SHGC and VLT, the algae samples were installed on a black chamber facing a south orientation (Figure 1). The algae samples were 1ft by 1ft flat panels with four varying algae cavity thicknesses and four different algae cell concentrations. The initial dense culture was named "pseudo 100%" to indicate 100% algae density. In the "pseudo 75%" culture, 25% of the initial algae was replaced with water. Similarly, in the "pseudo 50%" culture, 50% of the initial algae was replaced with water. Lastly, in the "pseudo 25%" culture, 75% of the initial algae was replaced with water.

The SHGC and VLT data were measured on a clear summer day on July 29, 2023 by assessing the radiation transmittance through the algae samples. The measurements were conducted using a pyranometer (Apogee SP510), photometer (Apogee SE421), and quantum meter (Apogee SQ521). A set of pyranometer, photometer, and quantum meter was installed on top of the chamber and measured incoming sunlight. Another set of sensors was installed inside the chamber behind the algae samples and measured the transmitted sunlight through them. The pyranometer, is commonly used to analyze the absorption and transmission of light in range of 385 nm to 2105 nm. This device determined the algae samples. The quantum meter measures photosynthetic photon flux density in range of 389 to 692 nm. The device assessed how much solar energy is transmitted through the algae samples. The photometer is specifically designed to measure light intensity from 0-150,000lux. This instrument provided daylight penetration through the amount of photosynthetically active radiation (PAR) absorbed by the algae samples at different concentrations. PAR is directly related to plant growth and therefore, only SHGC and VLT were presented in this paper.

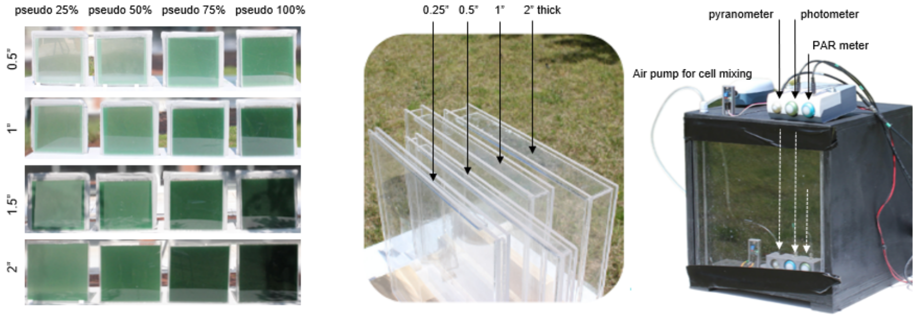


Figure 1: SHGC and VLT Experiment Set-up Consisting of the Algae Façade Samples, a Testing Chamber, and Data Measuring Sensors. Source: (Kyoung Hee Kim 2023).

Table 1 provides a comprehensive overview of measurements conducted across various testing scenarios. The data reveals a clear correlation between algae cell densities and both SHGC and VLT. The microalgae medium with the lowest cell concentration exhibits the highest SHGC and VLT values, while the pseudo 100% microalgae culture shows the lowest values. The SHGC demonstrates non-linear reduction as algae density increases across different thicknesses. The 2-inch cavity exhibits less sensitivity to SHGC changes for different microalgae densities, particularly in the high concentration region, when compared to other thicknesses. The influence of microalgae density on VLT also showed a clear correlation. The reduction in density from 100% to 25% results in substantial VLT.

In parallel with SHGC, the 2-inch cavity demonstrates reduced sensitivity in VLT changes for microalgae density than other thicknesses. Additionally, the data reveals a clear correlation between algae cavity thickness and both SHGC and VLT. As the thickness of the algae cavity increased from 0. 5 inches to 2 inches, both SHGC and VLT decreased. Within the range of 0. 5 to 1. 5 inches, both SHGC and VLT exhibit higher sensitivity to changes in VLT compared to the 2-inch thickness. The light-to-heat gain ratio (VLT/SGHC) can be used to assess the efficiency of a glazing system in blocking summer solar gains while maximizing daylight penetration.

A higher light-to-heat gain ratio indicates better energy efficiency. As the algae cavity thickness decreases, the light-to-heat gain ratio increases. For high cell concentration, the 2-inch thickness exhibited reduced daylight penetration. This characteristic is particularly beneficial for spaces that necessitate different levels of privacy or where glare negatively affects productivity and well-being.

Table 1: Experimental Results: Investigating the Influence of Cavity Thickness and Microalgae Density on SHGC and VLT. Source: (Authors 2023).

Metrics	*Pseudo cell density*	*Thickness*			
		0.5 inch	*1 inch*	*1.5 inches*	*2 inches*
SHGC	*25%-Microalgae*	0.71	0.60	0.51	0.40
	50-Microalgae	0.63	0.47	0.37	0.28
	75-Microalgae	0.48	0.36	0.30	0.21
	100-Microalgae	0.45	0.34	0.29	0.10
	Water	0.73	0.80	0.82	0.86
VLT	*25%-Microalgae*	0.64	0.55	0.39	0.96
	50-Microalgae	0.46	0.30	0.16	0.23
	75-Microalgae	0.27	0.16	0.06	0.06
	100-Microalgae	0.185	0.086	0.028	0.005
	Water	0.73	0.80	0.82	0.96

Figure 2 visually represents the effective SHGC and VLT across various densities and cavity thicknesses. Additionally, polynomial trendlines are incorporated into the figure. The data points allowed us to establish the relationships between solar gain, daylight penetration, and cell density for different cavity thicknesses. The inclusion of these mathematical relationships enhances our understanding of how SHGC and VLT varies with microalgae density across different cavity thicknesses, providing valuable insights into the nuanced interplay between these factors.

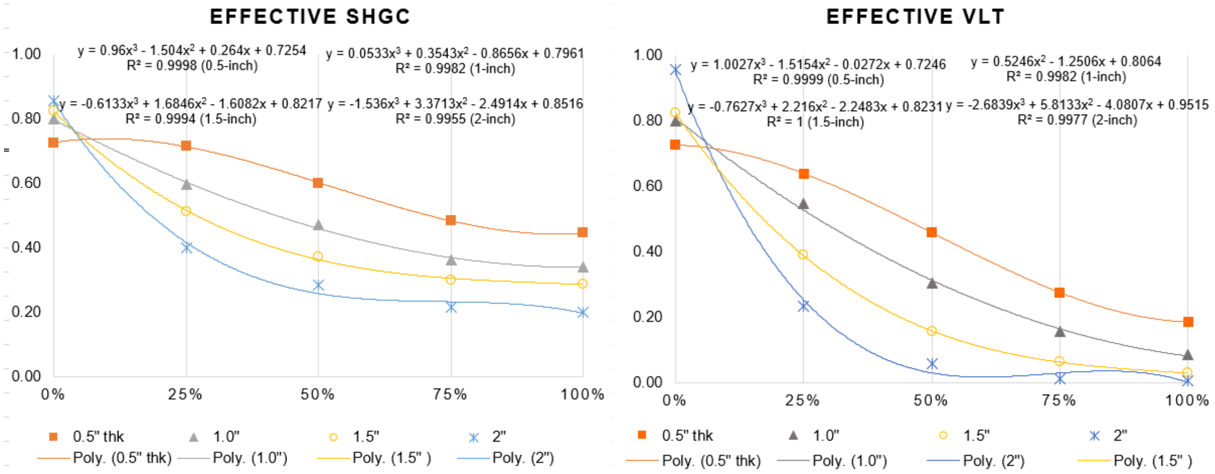


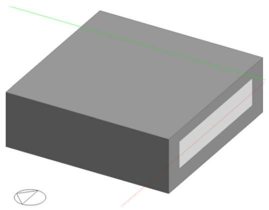
Figure 2: Correlation between microalgae density and effective SHGC (left) and VLT (right). Source: (Authors 2023).

3.0 ENERGY SIMULATION

The impact of using a microalgae facade was investigated in nine different cities, including Miami, Houston, Los Angeles, Charlotte, New York, Boston, Minneapolis, Fargo, and Fairbanks. These cities represent different climate zones in accordance with ASHRAE 90.1. The comparison was conducted through DesignBuilder software (Designbuilder n.d.). DesignBuilder is a comprehensive software tool employed for the meticulous modeling of diverse facets within the realm of building design through the EnergyPlus engine. It adeptly facilitates the dynamic simulation of energy consumption across various building typologies. This simulation encompasses heating, cooling, lighting, appliances, domestic hot water, and other performance metrics. DesignBuilder was harnessed to model the intricate physics of the building, incorporating considerations such as materials, architectural features, as well as heating and cooling systems and lighting systems (Eisabegloo, Haghshenas and Borzoui 2016). Moreover, DesignBuilder exhibits proficiency in Computational Fluid Dynamics (CFD) modeling and can accurately compute lighting rates within a given spatial context. Leveraging climatic data files, the software excels in the precise calculation of energy-related parameters, encompassing energy reception, wastage, and consumption, tailored to the unique climatic conditions of the site (Eisabegloo, Haghshenas and Borzoui 2016). An exemplary attribute of the DesignBuilder software lies in its user-friendly interface, characterized by an excellent Graphical User Interface (GUI). Noteworthy is the software's self-sufficiency, as it operates autonomously without necessitating additional software dependencies. This attribute enhances the accessibility and usability of DesignBuilder, making it a versatile and efficient tool for architects, engineers, and researchers engaged in the intricate domain of building design and energy simulation (Eisabegloo, Haghshenas and Borzoui 2016).

The primary objective of this investigation was to evaluate the energy performance of a microalgae facade in comparison to a glass window that is in compliance with standards, taking into account different climate zones. The study used a single-zone space with dimensions of 30 feet in width, 30 feet in length, and 10 feet in height. The building had a Window to Wall Ratio (WWR) of 40% on the south-facing facade only. The remaining building envelopes, including the east, west, and north facades, as well as the floors, were set as adiabatic, meaning no energy flows were allowed except through the south facade. The building schedule followed an office schedule, which calculated the energy consumption associated with office activities. The HVAC system was assigned with variable-air-volume (VAV) terminal units, and the lighting power density was set at 0. 7W/sq. ft in accordance with ASHRAE 90. 1 standard. Table 2 summarizes the simulation setup and parametric variables. The parametric variables included nine different cities and eight different SHGCs, which represent various algae cell concentrations.

Table 2: Simulation Set-up and Parametric Analysis Variables. Source: (Authors 2023)

	Microalgae building	*Reference building per ASHRAE 90.1 standards*
Climate zones in accordance with ASHRAE 90.1	1A_Miami, FL (very hot humid) 2A_Houston, TX (hot humid) 3C_Los Angeles, CA (warm marine) 3A_Charlotte, NC (warm humid) 4A_ New York, NY (mixed humid) 5A_Boston, MA (cool humid) 6A_Minneapolis, MN (cold humid) 7_Fargo, ND (very cold) 8_Fairbanks, _AK (subarctic)	
% WWR	40%	
Window attributes	SHGC-0.1, U-0.48	1AB_ SHGC-0.23, U-0.5

	SHGC-0.2, U-0.48 SHGC-0.3, U-0.48 SHGC-0.4, U-0.48 SHGC-0.5, U-0.48 SHGC-0.6, U-0.48 SHGC-0.7, U-0.48 SHGC-0.8, U-0.48	2AB_ SHGC-0.25, U-0.45 3ABC_SHGC-0.25, U-0.42 4ABC_ SHGC-0.36, U-0.36 5AB_ SHGC-0.38, U-0.36 6AB_ SHGC-0.38, U-0.34 7_ SHGC-0.4, U-0.29 8_ SHGC-0.4, U-0.26
Other simulation settings	Gross floor area: 900ft^2 Operation schedule: office Other enclosure requirements, lighting & HVAC & plug load requirements per ASHRAE 90.1 standard	

The results of the simulation are presented in Table 2. The highlighted numerical values in this analysis correspond to the glazing recommendations outlined by ASHRAE 90.1 for distinct climate zones. These simulations aim to provide insights into the energy efficiency of dynamic microalgae facades in diverse climatic contexts.

The results indicated that microalgae facades yield a significant reduction in energy consumption, ranging from 4% to 12%, across various climates compared to counterpart window systems. The highest reduction in energy consumption was observed in Miami (very hot and humid; 1322.92 kWh savings), followed by Minneapolis (cold and humid; 1199.24 kWh savings), Boston (cool and humid; 1141.80 kWh savings), New York (mixed and humid; 1082.31 kWh savings), Charlotte (warm and humid; 1007.87 kWh savings), Houston (hot and dry; 886.25 kWh savings), and Los Angeles (warm and marine; 378.94 kWh savings). The most substantial potential for energy savings was identified in the Miami climate (Very hot and humid). The microalgae facades demonstrated an annual energy consumption of 19682.94 kWh, whereas the counterpart building consumed 20991.22 kWh. As a result, the microalgae facades achieved a 7% energy savings (1322.92 kWh) due to their lower SHGC throughout the seasons. In mixed climate zones, the energy consumption for the reference building with ASHRAE windows in New York was calculated to be 10393.47 kWh, while the microalgae building had an annual energy consumption of 9311.45 kWh, which can be attributed to the dynamic adaptability of microalgae facades in regulating solar gains based on seasonal variations. This positive impact is prevalent in most climates, excluding Fairbanks, where the U-factor plays an important role in heating dominant. Specifically, during the heating dominant seasons in Fairbanks (January through April and September through December), the microalgae facade with a U-value of 0. 48 and SHGC of 0. 8 had a higher energy consumption of 11405.15 kWh compared to the referenced window with a U-value of 0. 26 and SHGC of 0. 4, which has an energy consumption of 11174.21 kWh. This results in a 2% increase (230.94 kWh) in energy consumption due to the microalgae facades' ability to maximize winter solar gain. During the cooling seasons (May through August), the microalgae window with a U-value of 0. 48 and dynamic SHGC has a lower energy consumption of 2350.14 kWh compared to the reference window with an energy consumption of 2402.60 kWh. This results in a 2% energy savings (51.58 kWh) due to the microalgae window's ability to block summer heat gain.

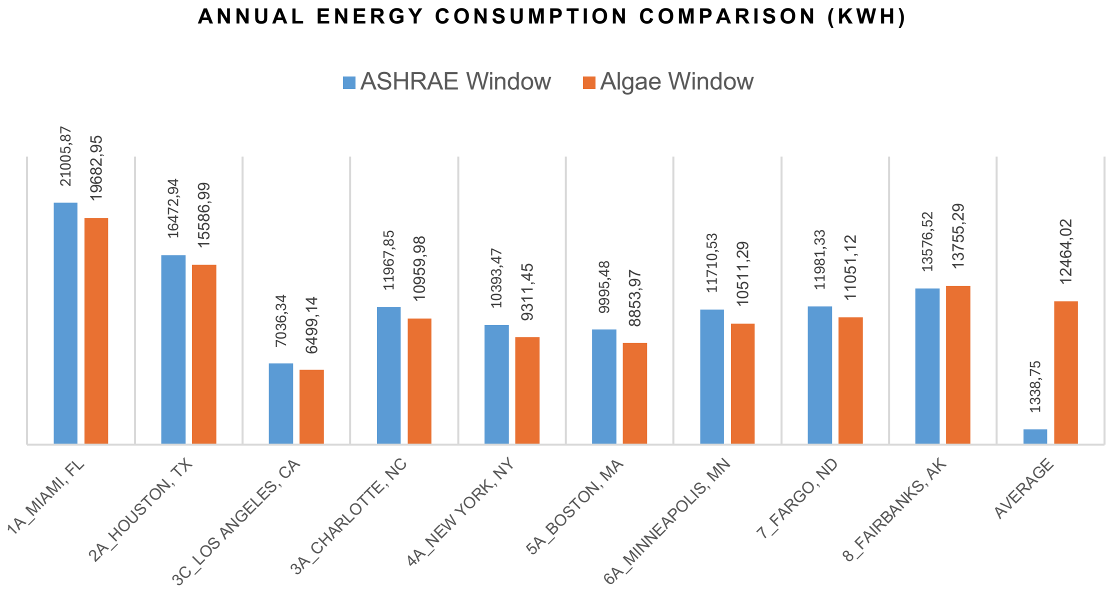


Figure 3: Simulation results: Investigating the influence of using microalgae façade on energy consumption (kWh) in different cities. Source: (Authors 2023).

CONCLUSION

A microalgae facade, with its unique features and positive impact on energy consumption and greenhouse gas reduction, as well as its ability to provide shading based on specific needs in climate conditions, is gaining prominence and deserves extensive research. This study aims to investigate the influence of various parameters and conditions on microalgae facades. The research involved measuring the effect of microalgae density and thickness on Solar Heat Gain Coefficient (SHGC) and Visible Light Transmittance (VLT) through various tests and sensors. Conducted in Charlotte, North Carolina on July 29, 2023, the study also utilized simulation techniques to compare the energy consumption of a building enclosed with a microalgae facade to a reference building with identical specifications but featuring conventional glazing in compliance with ASRHAE 90.1 requirements. The study building was 30 feet by 30 feet building with a height of 10 feet, having 40% openings on the south façade only.

Results revealed that altering microalgae density from 100% to 25% led to changes in SHGC and VLT, consequently impacting on the building's energy consumption. The substantial difference in SHGC values highlights the dynamic nature of this architectural feature, allowing for adjustments according to the building's requirements by manipulating microalgae density. Comparative analysis of energy consumption between a building using a microalgae facade and one using ASRHAE 90.1 glazing demonstrates that, in almost all climates, the use of a microalgae facade results in a reduction in energy consumption. The microalgae facade, particularly with dynamic SHGC, exhibited a 6% to 12% decrease in energy consumption compared to a building using ASHRAE-recommended glazing across the majority of the climate zones studied. These findings underscore the potential of microalgae facades to contribute to sustainable and energy-efficient building practices.

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