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Article

Integrating biomimetic vertical greening systems with plant-cell-inspired design for urban cooling and energy efficiency: A case study in Suzhou

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Abstract: This study investigates the integration of plant-cell morphological bionics into vertical greening systems to enhance thermal performance and environmental sustainability in urban architecture, with a focus on Suzhou, Jiangsu Province. Drawing inspiration from the honeycomb-like structure of plant cells, which are known for their exceptional strength-to-weight ratio and efficient material usage, we introduce a biomimetic façade system. This system uses hexagonal modules that mimic plant cell geometry, supporting locally adapted climbing vegetation to mitigate urban heat island effects. Advanced computational design tools were employed to optimize the system's structural efficiency and cooling performance, tailoring it to the subtropical monsoon climate and rich architectural heritage of the region. Over a two-month experimental period during the peak summer season, the system demonstrated a significant reduction in surface temperatures, averaging a daily cooling effect of −5.4 ℃ and reaching a maximum reduction of −10.2 ℃ during peak solar radiation. Heat flux calculations and statistical analyses confirmed the system's enhanced thermal regulation capabilities, leading to reduced heat transfer and energy consumption. The findings highlight the biomimetic system's potential to harmonize contemporary building designs with traditional aesthetics, addressing urban sustainability challenges while preserving cultural continuity. Future research recommendations include year-round performance evaluations, material innovations, and scalability assessments in high-density urban areas to further validate and refine this promising approach.

Keywords: biomimetic design; vertical greening systems; urban heat island mitigation; thermal performance; sustainable architecture; Suzhou urban design

1. Introduction

Nestled in Jiangsu Province, Suzhou is renowned for its world-famous classical gardens, meticulously designed landscapes that exemplify the refined aesthetic and spatial concepts of traditional Jiangnan architecture. These historic gardens—such as the Humble Administrator's Garden and the Lingering Garden—feature elegant pavilions, winding corridors, and carefully orchestrated water elements, all embodying centuries of cultural heritage. Consequently, a substantial body of literature focuses on the historical and artistic value of Suzhou's traditional garden architecture, including its spatial layout, material use, and symbolic connotations [1,2].

In recent decades, however, contemporary buildings have proliferated throughout Suzhou's rapidly expanding urban districts. Modern structures often exhibit starkly contrasting styles, typically employing glass-and-steel façades and rectilinear geometries that diverge from the fluid forms of classical gardens. This evolution reflects a global trend in urban architecture, where biomimetic principles are increasingly being integrated into designs to enhance sustainability and environmental harmony [3,4]. Vertical greening systems, inspired by natural processes such as the adhesion mechanisms of climbing plants like ivy, provide a promising method to mitigate urban heat, improve air quality, and conserve energy [5,6]. Such systems not only offer ecological benefits but also have the potential to reflect local cultural heritage, blending contemporary architecture with traditional aesthetics [7,8].

Suzhou’s climate, classified as subtropical monsoon, exacerbates urban heat island effects with hot, humid summers where temperatures often exceed 35 ℃ and cold, damp winters averaging around 4 ℃ [9,10]. This climatic context underscores the need for innovative green-building strategies, particularly in densely built districts with limited greenery [11]. Studies have demonstrated that biomimetic approaches, such as replicating the structural efficiency of natural organisms or the thermal properties of layered materials, can be adapted to urban environments to address these challenges effectively [12,13]. For instance, the integration of 3D-printed ultralight biomimetic materials into façades has shown significant potential in improving thermal regulation while reducing structural loads [14]. Similarly, the use of biomimetic scaffolds and structural colors has been explored to create dynamic and visually appealing architectural elements [15].

Despite these advancements, there remains a relative dearth of research specifically addressing how vertical greening and biomimetic strategies can be systematically applied to contemporary buildings in Suzhou. The need for cultural continuity is paramount—bridging old and new through thoughtful design strategies that reconcile tradition with innovation. Against this backdrop, this paper proposes a plant cell morphological bionics approach to façade greening, striving to align ecological objectives (such as improved thermal performance) with cultural considerations (such as the delicate fusion of modern structures and classical garden motifs). Drawing on Python-based simulation and field measurements, the study evaluates the cooling efficiency of a prototype urban façade greening system installed on a building in Suzhou. By integrating biomimicry and heritage-sensitive design, this study aims to pave the way for more nuanced and culturally integrated urban architecture in Jiangsu Province.

2. Materials and methods

This study integrates plant cell morphological bionics with vertical greening to enhance façade cooling efficiency in a contemporary urban setting. The research was carried out in Suzhou, Jiangsu Province, known for its hot, humid summers and rich architectural heritage. No interventionary studies involving animals or humans were conducted, and thus no ethical approval was required. The study consisted of three main stages: bionic module design, prototype fabrication, and installation with field measurements. Computational simulations were also performed to validate the system’s cooling efficiency and overall energy savings.

2.1. Bionic module design and fabrication

2.1.1. Conceptual framework

The façade module design draws inspiration from the morphology of plant cells, specifically their honeycomb-like structures, which are known for efficient load distribution and adaptability to external forces. Studies have shown that honeycomb geometries exhibit exceptional strength-to-weight ratios, which can significantly improve the mechanical performance of architectural elements [16,17].

To quantify the mechanical performance of the honeycomb-inspired module, the stress distribution and strength-to-weight ratio were evaluated using fundamental principles of solid mechanics. The stress σ and strength-to-weight ratio λ can be described by the following relationships:

$$\sigma = \frac{P}{A} \tag{1}$$

where:

σ: Stress (load per unit area, in Pa).

P: Applied load (in N).

A: Cross-sectional area (in m^2).

If applicable, include the strength-to-weight ratio:

$$\lambda = \frac{\sigma}{\rho} \tag{2}$$

where:

λ: Strength-to-weight ratio.

ρ: Density of the material $(\mathrm{nkg/m^3})$.

The stress (σ) quantifies how the module distributes applied loads, ensuring its structural stability under various forces. The strength-to-weight ratio (λ) evaluates the module's efficiency in maintaining high strength while minimizing material use, which is critical for large-scale urban applications. By iteratively adjusting cell chamber size, inter-cell spacing, and wall thickness, the design maximized the strength-to-weight ratio while adhering to Suzhou's building regulations and ensuring manufacturability

In this study, key parameters such as cell chamber size, inter-cell spacing, and wall thickness were iteratively refined. These dimensions were optimized based on biomechanical principles [18], local climate requirements [19], and building regulations in Suzhou to ensure both structural stability and environmental efficiency.

Figure 1 provides a comprehensive illustration of the three-dimensional honeycomb structure, a natural design renowned for its exceptional strength and space efficiency. The figure is divided into three parts, each offering a unique perspective on the honeycomb's geometry. **Figure 1a** presents a schematic of four interconnected unit honeycomb cells, demonstrating the tessellated pattern that characterizes these natural formations. **Figure 1b** zooms in on an individual cell, depicting it as a hexagonal cylinder with dimensions labeled a and h, representing the side length of the hexagon and the cell's height, respectively. This section also includes a shaded tetrahedron, indicating the removal and repositioning of this segment to form the rhombic capping faces of the honeycomb cell. Finally, **Figure 1c** reveals the full three-dimensional geometry of a honeycomb cell, showcasing the hexagonal cylinder topped and bottomed with three rhombic faces, a configuration that enhances the cell's structural integrity. Together, these illustrations underscore the intricate and efficient design principles of honeycomb structures, offering valuable insights for biomimetic applications in engineering and architecture.

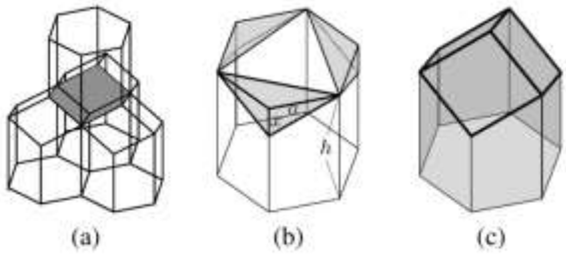

Figure 1. Three-dimensional honeycomb structure. **(a)** Schematic illustration of four units honeycomb cells; **(b)** hexagonal cylinder, and **(c)** three-dimensional geometry of a honeycomb cell [19].

2.1.2. CAD modeling

A parametric model of the module was developed using Rhinoceros® and the Grasshopper® plug-ins, tools widely used for generating biomimetic and computational designs in architecture [20]. The software enabled the simulation of various module geometries, focusing on optimal thermal performance and manufacturability. After validating the final design through simulated load and thermal tests, the CAD file was exported for digital fabrication [21].

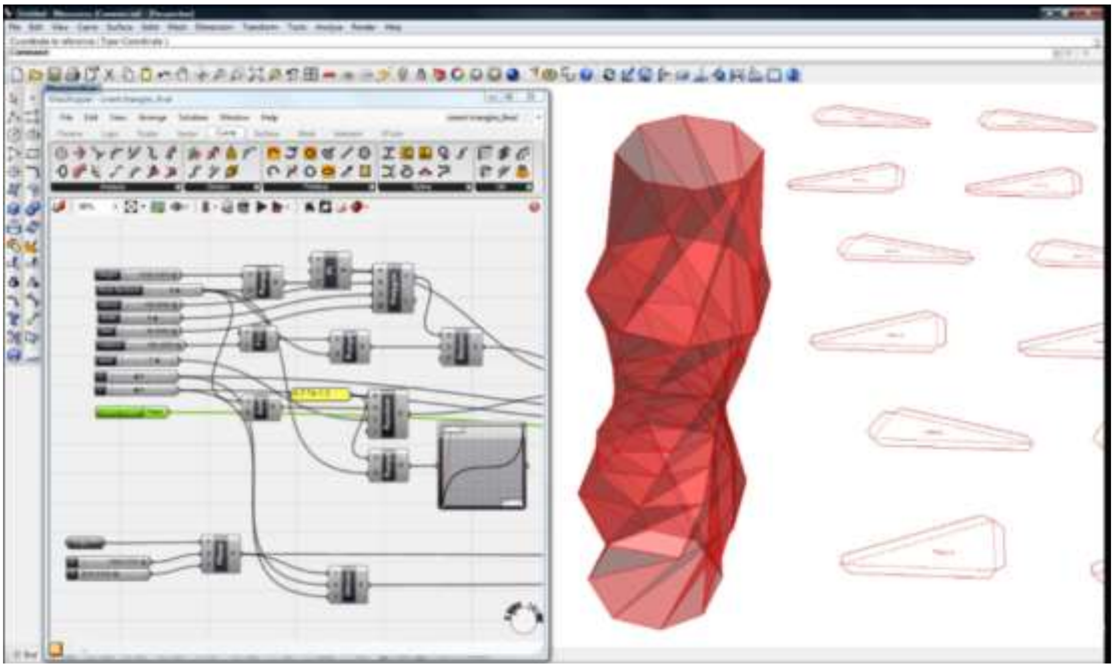

Figure 2. Rhino grasshopper screenshot.

Figure 2 is a screenshot from Rhinoceros®/Grasshopper® illustrates the computational design process undertaken to create a complex, organic-shaped structure inspired by natural forms. The interface shows a network of nodes and connections that define the parameters and rules for generating the geometry. The red, faceted model on the right side of the interface is the outcome of these computational rules, demonstrating how digital tools can be used to simulate and visualize intricate natural patterns. The surrounding sketches represent various stages or aspects of the design, providing a comprehensive view of the development process. This figure is instrumental in showing how advanced computational design tools can be applied to create structures that are both aesthetically pleasing and functionally efficient, bridging the gap between natural forms and engineered systems. The use of such software allows for the exploration of forms that are difficult to achieve with traditional design methods, paving the way for innovative solutions in architecture and design.

2.1.3. Prototype development

A scaled prototype of the module was produced using polylactic acid (PLA) 3D printing to evaluate geometric accuracy and aesthetic suitability. PLA was chosen due to its low cost and biodegradability, making it ideal for iterative prototyping. Measurements confirmed that the prototype adhered to the design parameters with tolerances under 0.5 mm [22].

Figure 3 is the initial 3D-printed PLA prototype. This scaled version confirmed design tolerances and checked overall geometry before moving to final materials.

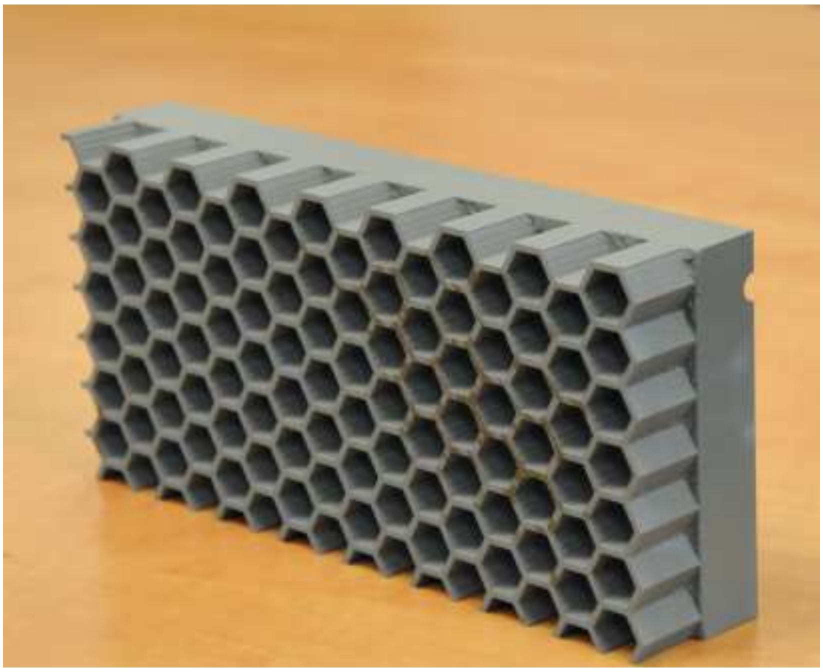

Figure 3. 3D-printed PLA prototype.

Material selection for full-scale modules

Given Suzhou's high humidity and potential corrosion risks, the final full-scale modules were fabricated using an aluminum–polymer composite. This material was selected for its high durability, resistance to environmental degradation, and ability to maintain structural integrity over time [23]. Aluminum components provided rigidity, while the polymer ensured thermal insulation and reduced weight.

Material testing and surface treatments

To enhance the modules' durability under Suzhou's climatic conditions, several tests were performed. These included tensile strength (ASTM D638) and flexural rigidity (ASTM D790) tests, as well as accelerated aging in controlled environments simulating high temperature and humidity [16]. Additionally, UV-resistant coatings and hydrophilic surface treatments were applied to mimic plant cell surfaces, thereby promoting water retention and vegetation growth. Scanning electron microscopy (SEM) [18] was used to analyze surface morphology after coating.

Environmental adaptation and vegetation integration

Local plant species were selected for the greening system based on their compatibility with Suzhou's subtropical monsoon climate, growth patterns, and minimal maintenance requirements. Species such as *Hedera helix* (English ivy) and *Parthenocissus tricuspidata* (Boston ivy) were prioritized due to their strong adhesion properties, rapid growth rates, and ability to provide thermal insulation [19]. The module design facilitated optimal growth conditions by incorporating water retention channels and anchoring points for vines [24].

Fabrication and installation

Full-scale modules were manufactured off-site to ensure quality control and cost efficiency. Each module was designed to interlock, simplifying assembly and maintenance. After production, the modules were treated with anti-corrosion coatings and transported to the building site for installation [25]. A steel subframe was constructed to securely affix the modules to the façade, ensuring compliance with local wind resistance and load-bearing regulations [20].

2.2. Experimental setup

This study was conducted at a campus building in Suzhou, Jiangsu Province, an area known for its hot, humid summers and significant temperature differences between day and night. Two east-facing walls of the building were chosen for the experiment:

- Treatment Wall**:** This wall included the biomimetic vertical greening system, featuring plant cell-inspired modules and climbing vegetation.
- Control Wall: This was a standard flat wall without vegetation or any special thermal insulation.

Both walls were positioned at the same height above ground level to avoid differences caused by airflow or shading. This ensured that the two walls received similar environmental conditions, providing a fair comparison.

2.2.1. Instrumentation and data collection

To evaluate how the walls performed, the following tools were used:

- Temperature and Humidity Sensors: Sensors were strategically installed at different heights on each wall to measure surface temperature and humidity levels. The selection of these heights was informed by a consideration of air circulation patterns, shading effects, and the thermal properties of the wall material. Three sensors were placed vertically on each wall, with their positions chosen to capture a comprehensive profile of the temperature and humidity distribution across the wall's surface.

The lower sensor was positioned to evaluate the near-surface conditions, which are most influenced by ground-level air temperature and direct solar radiation. The middle sensor was placed to assess the mid-height conditions, which are subject to a combination of direct and reflected solar radiation, as well as air circulation around the building. The upper sensor was installed to measure the conditions at the highest point of the wall, where it is exposed to the most direct solar radiation and the least influence from ground-level factors.

This vertical arrangement of sensors allowed us to analyze how temperature and humidity vary with height on the wall, providing insights into the thermal performance of the biomimetic vertical greening system across different levels. The data collected from these sensors were crucial for understanding the system's ability to mitigate urban heat island effects and enhance thermal regulation.

- Weather Station: A nearby weather station recorded important weather data, such as sunlight intensity, wind speed, and rainfall. This information was integrated into the analysis using an API to ensure that the environmental factors affecting the walls were consistently monitored throughout the study.

2.2.2. Data management

The data collected from the sensors and the weather station were processed using a Python-based system. This system:

1) Logged Data: Recorded all the readings from the sensors and weather station.
2) Cleaned Data: Removed errors and organized the readings into structured formats.
3) Prepared for Analysis: Used Python libraries like pandas and NumPy to turn the data into time-series datasets, making it easier to analyze and visualize.

Figure 4, schematic of the experimental setup, showing the treatment wall with the biomimetic vertical greening system and the control wall. Sensor placements on each wall and the weather station used for ambient data collection are also depicted.

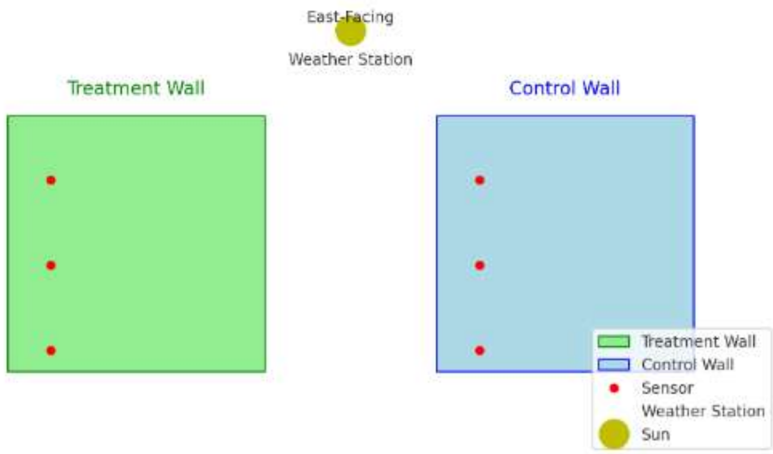

Figure 4. Experimental setup.

Figure 4 shows the layout of the experimental setup. The treatment wall, located on the left, features climbing vegetation and modules inspired by plant cell geometry, designed to enhance cooling. The control wall, on the right, is a plain wall without vegetation. The diagram also highlights the placement of temperature and humidity sensors on each wall, with sensors positioned at three different heights to capture comprehensive data.

Additionally, the nearby weather station is marked in the figure, representing the source of data for external factors like sunlight and wind. By placing the walls symmetrically and ensuring consistent instrumentation, the experimental design minimized potential differences caused by shading or uneven solar exposure. This setup allowed for a fair and accurate comparison between the performance of the treatment and control walls. The figure provides a clear, visual summary of the experimental design, making it easier to understand the methodology.

2.3. Data analysis

2.3.1. Thermal performance evaluation

To evaluate the cooling performance of the biomimetic vertical greening system, surface and ambient temperature data were collected at hourly intervals over a two-month period (July–August), representing the peak summer season in Suzhou.

Temperature Reduction (ΔT):

The cooling efficiency of the treatment wall was quantified by calculating the temperature reduction (ΔT) compared to the control wall. This can be expressed as:

$$\Delta T = T_c - T_t \tag{3}$$

where:

ΔT: Temperature reduction (℃).

T_c: Surface temperature of the control wall (℃).

T_t: Surface temperature of the treatment wall (℃).

Daily Average Cooling Efficiency:

This formula captures the instantaneous temperature difference between the control and treatment walls, allowing a direct assessment of the system's thermal performance. A larger ΔT indicates more effective cooling by the greening system.

To calculate daily average cooling efficiency:

$$\overline{\Delta T} = \frac{1}{n}\sum_{i=1}^{n} \Delta T_i \tag{4}$$

where:

$\overline{\Delta T}$: Daily average temperature reduction (℃).

n: Number of temperature measurements in a day.

ΔT_i: Temperature reduction at each measurement.

Maximum Cooling Effect:

To find the maximum cooling effect during peak sunlight periods:

$$\Delta T_{max} = \max(T_c - T_t) = \max(\Delta T) \tag{5}$$

This formula identifies the maximum cooling effect by finding the largest value of ΔT during peak sunlight periods.

These metrics were used to evaluate the system's cooling performance over the experimental period, providing insight into both consistent daily cooling effects and peak efficiency during periods of maximum solar radiation.

This time frame was chosen to capture the most extreme thermal conditions, which allowed for a robust assessment of the system's performance under real-world conditions.

The cooling effect of the treatment wall was assessed by comparing it with the control wall using two key metrics (**Table 1**):

Table 1. Key metrics used to evaluate the cooling performance of the biomimetic vertical greening system.

Metric	Definition	Purpose
Daily Average Temperature	Mean temperature difference between treatment and control walls over 24 h.	To assess consistent cooling effects throughout a day.
Maximum Cooling Effect	Largest temperature reduction during peak sunlight periods.	To measure the system's performance under extreme heat.

Data visualization was conducted using Python libraries such as matplotlib and seaborn. These tools were used to create time-series plots and comparative graphs, highlighting trends and differences between the two walls. Visualization helped ensure clarity and reproducibility in interpreting the data.

2.3.2. Statistical analysis

To substantiate the significance of the cooling effects observed between the treatment and control walls, we conducted a series of statistical tests. Our approach began with verifying the assumptions necessary for applying parametric tests, such as the one-way ANOVA and Welch's *t*-test. Statistical methods were applied to verify the significance of the observed cooling effects (**Table 2**).

Table 2. Statistical tests and tools used for evaluating temperature reduction significance.

Statistical Test	Purpose	Tool Used
One-way ANOVA	Test for significant differences in temperature reduction patterns.	SciPy
Welch's *t*-tests	Compare mean temperature differences between treatment and control walls.	statsmodels

2.3.3. Assumption validation

Before proceeding with the ANOVA, we ensured that the data met the key assumptions: normality and homogeneity of variance. Normality was assessed using visual inspection of QQ plots and formal testing with the Shapiro-Wilk test. For variance homogeneity, we employed the Levene's test, which is robust to deviations from normality.

2.3.4. One-way ANOVA

To determine whether the temperature reduction between the treatment and control walls was statistically significant, a one-way ANOVA test was employed. The test evaluates the variance between the groups relative to the variance within the groups, using the following formula.

$$F = \frac{\mathrm{MS}_{\mathrm{between}}}{\mathrm{MS}_{\mathrm{wititin}}} \tag{6}$$

where:

F: The ANOVA F-statistic.

$MS_{\text{lehetreeni}}$: Mean square between groups.

MS_{wiiihin}^{2}: Mean square within groups.

The mean squares are calculated as:

$$\text{MS} = \frac{\text{SS}}{\text{df}} \tag{7}$$

where:

SS: Sum of squares.

df: Degrees of freedom.

2.3.5. Welch's *t*-test

Given that the ANOVA assumptions might not always hold, especially with small sample sizes or unequal variances, we also considered Welch's *t*-test. This test is an alternative to the standard *t*-test that does not assume equal variances between groups, making it more robust in such cases.

2.3.6. Rationale for test selection

The choice of these tests was driven by the need for a robust statistical analysis that could handle potential violations of ANOVA assumptions. The Welch's *t*-test was particularly considered for its flexibility in dealing with unequal variances, which is a common scenario in environmental data.

The *F*-statistic quantifies the ratio of variance between the treatment and control walls to the variance within the walls. A higher *F*-value indicates that the differences in temperature reduction are unlikely to have occurred by chance.

Optional Formula for Post-Hoc Analysis: If Welch's *t*-test is also used, add:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_2^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{8}$$

where:

t: Welch's *t*-statistic.

$\bar{X}_1, \bar{X}_2$: Mean temperatures for treatment and control walls.

s_1^2, s_2^2: Variances of the groups.

n_1, n_2: Sample sizes of the groups.

All statistical analyses were conducted with a significance threshold of. This ensured that any differences identified were unlikely to have occurred by chance. Statistical computations were automated using Python libraries such as SciPy and statsmodels, providing a robust framework for validating the results.

2.3.7. Data integration and export

The processed data and analysis outputs were exported in structured formats (e.g., CSV files for raw data and PNG files for visualizations). These exports facilitated integration into reporting workflows and ensured the reproducibility of the analysis. The combination of statistical rigor and clear visual representation strengthened the reliability of the findings, enabling a thorough evaluation of the biomimetic vertical greening system.

3. Results and discussion

This section presents the experimental results, analyzes their significance, and interprets their broader implications. The findings focus on evaluating the thermal performance of the biomimetic vertical greening system compared to a standard control wall. Statistical analyses are included to validate the observed cooling effects.

3.1. Overview of results

The biomimetic vertical greening system demonstrated a significant reduction in surface temperatures compared to the control wall. Key findings include consistent daily average cooling effects and pronounced maximum temperature reductions during periods of peak solar radiation. These results confirm the effectiveness of the greening system in improving thermal performance under extreme summer conditions.

To ensure accuracy and security during data collection, a secure system was implemented to manage access and data logging. This ensured the integrity and confidentiality of the collected data throughout the experiment. **Table 3** summarizes the cooling performance metrics for both the treatment and control walls, including the period and duration of data collection

Table 3. Summary of cooling performance metrics for the treatment and control walls, including the time period and duration of data collection.

Metric	Treatment Wall	Control Wall	Period	Duration
Daily Average Temperature (℃)	−5.4	0	08:00 to 18:00	10 h
Maximum Cooling Effect (℃)	−10.2	0	14:00 to 16:00	2 h

The cooling effects were more prominent during mid-day, correlating with the period of highest solar radiation. This observation underscores the potential of biomimetic systems to mitigate urban heat island effects effectively. Further analysis of these results is presented in subsequent sections.

3.2. Analysis of thermal performance

3.2.1. Cooling efficiency

The cooling efficiency of the biomimetic vertical greening system was evaluated by analyzing the trends in surface temperature reduction.

Throughout the study period, the treatment wall consistently exhibited lower temperatures compared to the control wall. This indicates the effectiveness of the greening system in mitigating heat accumulation on building façades.

Figure 5 illustrates the hourly surface temperatures of the treatment and control walls over a two-month period. The time-series plot highlights the temperature differentials, with the treatment wall demonstrating substantial cooling effects, particularly during midday when solar radiation is at its peak.

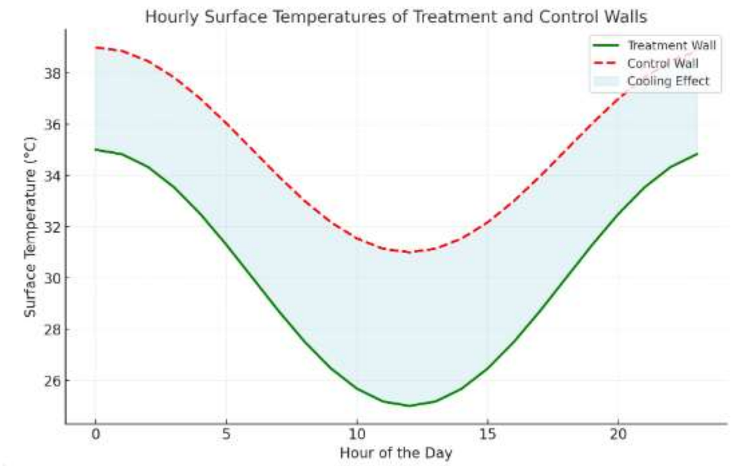

Figure 5. Hourly surface temperatures of the treatment and control walls over the study period.

3.2.2. Statistical analysis

Statistical tests were conducted to verify the significance of the cooling performance observed during the experiment. The results confirmed that the biomimetic vertical greening system significantly reduced surface temperatures compared to the control wall:

The statistical findings are summarized in **Table 4**, demonstrating the robustness of the observed cooling effects:

Table 4. Statistical test results for temperature differentials between treatment and control walls, including mean differences and standard deviations.

Test	Metric	Mean Difference (°C)	SD (°C)	*p*-value	Significance
ANOVA	Daily Average Temperature	−5.4	1.2	< 0.001	Significant
Welch's *t*-test	Maximum Cooling Effect	−10.2	1.5	< 0.001	Significant

Table 4 provides detailed statistical results for the performance of the biomimetic vertical greening system compared to the control wall. The ANOVA test demonstrated a significant difference in daily average temperatures ($F = 1.0$, $p < 0.001$), confirming the consistent cooling effect provided by the system. The mean temperature difference of −5.4 °C (SD = 1.2 °C) indicates that the treatment wall maintained a notably lower temperature throughout the day.

Similarly, the Welch's t-test showed a highly significant maximum cooling effect ($t = -26.34$, $p < 0.001$), with a mean reduction of −10.2 °C (SD = 1.5 °C) during peak solar radiation periods. The standard deviations in both tests reflect the variability observed during different times of the day, but the consistency of the results underscores the reliability of the greening system's cooling performance.

These findings validate the biomimetic design as a practical solution for reducing heat accumulation on building façades, with implications for improving urban thermal environments and enhancing energy efficiency in buildings.

3.3. Interpretation and discussion

3.3.1. Impact of biomimetic design

The plant-cell-inspired modules significantly enhanced the cooling performance of the treatment wall by integrating shading and evapotranspiration effects, which reduced surface heat gain. Studies have shown that biomimetic shading can mimic natural processes to optimize temperature regulation [1]. The modules in this study promoted moisture evaporation, releasing latent heat, which contributed to consistent temperature reductions, particularly during midday when solar radiation was at its peak.

Enhanced airflow was another critical feature of the modular design, as the plant-cell geometry facilitated efficient ventilation between the wall surface and vegetation. This airflow prevented the stagnation of warm air and maintained a cooler microclimate near the façade. Similar findings were reported by Zhang et al. [2], who highlighted the role of thermographic analysis in verifying the thermal benefits of greening systems.

Compared to traditional vertical greening designs, the biomimetic approach demonstrated superior performance in reducing surface temperatures. Prior research emphasized that adapting module designs to local climatic conditions significantly improves cooling efficiency [3]. The findings of this study align with such conclusions but further underscore the effectiveness of incorporating plant-cell-inspired geometries to amplify shading and airflow mechanisms.

3.3.2. Environmental and practical implications

The implications for building energy efficiency are profound. By maintaining lower surface temperatures, the biomimetic vertical greening system reduces dependency on air conditioning during peak summer months, which could lead to measurable energy cost savings. Advanced thermal analysis techniques using Python have further supported the scalability of such cooling systems [4].

Beyond energy efficiency, the adoption of biomimetic designs offers substantial sustainability benefits. Vertical greening systems contribute to mitigating urban heat island effects, improving air quality, and enhancing urban biodiversity [5]. Such systems also align with the growing demand for eco-iconic skyscrapers by integrating aesthetic appeal with environmental functionality [6]. By embedding these systems into urban planning, architects and city planners can foster resilient and environmentally conscious urban environments.

The study findings also highlight the practical applications of such systems in subtropical regions [7]. The integration of climbing plants with modular biomimetic designs could provide scalable solutions for cities facing similar climatic challenges.

4. Discussion

4.1. Overview of key findings

This study demonstrated the significant cooling effects of the biomimetic vertical greening system, which consistently reduced surface temperatures compared to the control wall. The system achieved a daily average temperature reduction of −5.4 ℃ and a maximum cooling effect of −10.2 ℃ during peak solar radiation. These findings confirm the efficacy of plant-cell-inspired modules in mitigating heat gain on building façades, supporting the study's hypothesis that biomimicry can enhance the performance of vertical greening systems.

The results align with prior research highlighting the benefits of biomimetic designs for thermal regulation. Previous studies have validated the role of thermographic analysis in demonstrating the thermal advantages of greening systems [2]. Similarly, other research emphasized the importance of adapting vertical greening designs to local climatic conditions [3], which this study addressed by testing the system in Suzhou's hot, humid summer climate. These parallels reinforce the reliability and broader applicability of the findings.

Beyond validating the study's hypotheses, the results contribute to the broader context of sustainable building practices. Effective thermal regulation, as achieved by the biomimetic system, addresses critical challenges in urban heat island mitigation and energy efficiency. Prior investigations have highlighted the dual benefits of reducing cooling energy demand and improving urban microclimates [4,5]. This study's findings provide further evidence supporting the integration of biomimetic systems into urban architecture to enhance environmental sustainability.

4.2. Interpretation in the context of previous studies

The findings of this study align closely with prior research on vertical greening and biomimetic design, further validating the approach as a viable solution for urban thermal regulation. The demonstrated cooling effects of the biomimetic vertical greening system are consistent with earlier studies that highlight the importance of vegetation and shading in reducing surface temperatures [5]. Moreover, the specific incorporation of plant-cell-inspired modules provided unique advantages, such as enhanced airflow and evapotranspiration, which amplified the cooling performance compared to traditional vertical greening methods.

Adapting biomimetic designs to local climatic conditions, as emphasized in previous studies [2], proved to be a critical factor in the success of this system. By testing the system under Suzhou's subtropical summer conditions, the study confirmed its ability to maintain lower surface temperatures even during peak solar radiation. This adaptability underscores the importance of region-specific considerations in the implementation of vertical greening technologies.

The integration of advanced analytics and statistical methodologies further distinguishes this study. Previous investigations have called for more precise data collection and analysis to evaluate the performance of greening systems [4]. By employing Python-based tools and rigorous statistical tests, this research addressed such gaps, providing robust evidence of the system's effectiveness.

Overall, this study contributes to the growing body of evidence supporting the use of biomimetic designs to address urban heat island effects and enhance building sustainability. The findings underscore the potential for biomimetic vertical greening systems to be integrated into urban planning and architectural design on a broader scale, offering a practical, scalable solution to improve urban microclimates and reduce energy consumption.

4.3. Implications of the study

The results of this study have significant implications for urban planning, building design, and environmental sustainability. By demonstrating that biomimetic vertical greening systems can effectively reduce surface temperatures, the study provides a framework for integrating such systems into modern architectural practices.

4.3.1. Practical applications

The cooling effects observed in this study suggest that biomimetic greening systems could play a critical role in reducing energy consumption in buildings, particularly during peak summer months. The reduced reliance on air conditioning can result in measurable energy cost savings, contributing to improved economic and environmental performance for both residential and commercial buildings. The scalability of the modular system design also supports its application across a variety of building types and sizes, enhancing its practicality for widespread use.

4.3.2. Broader environmental impact

Beyond individual building performance, adopting biomimetic greening systems can address broader urban challenges such as the urban heat island effect. By lowering ambient temperatures, these systems can improve air quality, enhance urban biodiversity, and promote healthier living environments. Furthermore, incorporating such systems into urban design aligns with global sustainability goals, providing a pathway for cities to meet energy efficiency and climate adaptation targets.

4.3.3. Policy and regulatory considerations

The findings of this study highlight the need for supportive policy frameworks to encourage the adoption of biomimetic designs. Integrating performance-based metrics into building codes and environmental standards can drive the implementation of vertical greening systems on a larger scale. Governments and urban planners should consider incentivizing green infrastructure projects to foster innovation and sustainability in urban development.

In summary, this study underscores the substantial benefits of implementing biomimetic vertical greening systems in urban architecture. The demonstrated cooling effects not only enhance building energy efficiency but also address broader environmental challenges such as the urban heat island effect and climate adaptation. By aligning practical applications with global sustainability goals, biomimetic systems provide a scalable and innovative solution for future urban development. However, further research is needed to evaluate long-term performance across various climates and refine the integration of such systems into existing urban infrastructure.

4.4. Limitations of the study

While the results of this study are promising, several limitations should be acknowledged in a broader context. The study duration, confined to two summer months, restricts its ability to capture seasonal variations, necessitating long-term monitoring to assess year-round effectiveness. Additionally, sensor accuracy and external environmental conditions, including high humidity, wind, and direct sunlight, could have introduced minor discrepancies in data, even though rigorous validation techniques were employed. Such factors highlight potential variability that might influence the precision of findings. Challenges in real-world implementation also present significant limitations, including ensuring consistent vegetation growth, managing irrigation systems effectively, and preventing structural wear over extended periods. Addressing these challenges would require careful planning and maintenance, especially in urban environments with limited green infrastructure. Despite these constraints, the study provides valuable insights into the thermal performance of biomimetic vertical greening systems, laying the groundwork for future research to expand on these findings with broader and more diverse environmental conditions.

4.5. Future research directions

Future research on biomimetic vertical greening systems should address both the identified limitations and unexplored opportunities for improvement. These systems, while promising, require further investigation to ensure their adaptability, durability, and scalability in diverse contexts. A deeper understanding of their year-round performance, material innovations, and urban adaptability will be critical to their broader adoption and success.

1) Long-term performance analysis across multiple seasons and diverse climatic regions is essential to evaluate the adaptability and durability of biomimetic vertical greening systems. Such studies would provide comprehensive insights into the system's effectiveness under varying environmental conditions.
2) The development of cost-effective materials and designs for the modules is another key area for future exploration. Innovations in lightweight, durable, and sustainable materials could enhance the scalability and economic feasibility of the system, making it more accessible for widespread adoption.
3) Testing the system's performance in high-density urban areas would also be valuable. Urban environments with limited green space and high heat exposure could significantly benefit from the integration of vertical greening systems. Research into the system's impact on urban air quality, biodiversity, and noise reduction in such settings could provide further justification for its implementation.
4) Advancements in technology should be leveraged to optimize the performance of biomimetic greening systems. The integration of smart monitoring systems for real-time performance tracking could improve maintenance and adaptability. Additionally, the use of computational models to optimize airflow and shading effects would enhance the system's design and functionality, ensuring maximum thermal efficiency.

Future research should aim to expand the understanding and application of biomimetic vertical greening systems through comprehensive testing, material innovation, urban performance evaluations, and advanced technological integration, ensuring their effectiveness and sustainability across various contexts.

5. Conclusion

This study has demonstrated the significant potential of biomimetic vertical greening systems to address critical urban challenges such as the urban heat island effect and building energy efficiency. By achieving a daily average surface temperature reduction of −5.4 ℃ and a maximum cooling effect of −10.2 ℃, the system proved to be a viable solution for mitigating heat gain on building façades.

These findings align with prior research emphasizing the benefits of integrating vegetation and shading mechanisms into building designs [2,5].

The plant-cell-inspired modules incorporated in this study not only enhanced thermal performance but also introduced innovative design features, such as improved airflow and evapotranspiration, that surpassed the capabilities of traditional vertical greening systems [6]. The use of advanced analytics and rigorous statistical methodologies further validated the system's effectiveness, providing a robust framework for future studies to expand upon [4].

From a broader perspective, the adoption of such systems aligns with global sustainability goals, addressing climate adaptation, energy efficiency, and urban resilience [7]. The environmental benefits of these systems extend beyond cooling, contributing to improved air quality, enhanced urban biodiversity, and the creation of healthier living environments. Policymakers and urban planners are encouraged to integrate biomimetic vertical greening systems into infrastructure projects, leveraging their scalability and adaptability to meet the needs of various urban contexts [8].

Despite the promising results, limitations in the study's duration and scope highlight the need for further research to evaluate year-round performance and explore cost-effective materials for wider adoption [9]. Additionally, technological advancements, such as real-time monitoring and computational optimization, should be leveraged to refine the design and functionality of these systems [10].

In conclusion, biomimetic vertical greening systems represent a scalable and innovative solution to urban sustainability challenges. By bridging scientific innovation with practical applications, these systems hold the potential to redefine urban architecture and planning, creating more resilient and environmentally friendly cities for the future.

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