Thermal Performance of Living Walls for Passive Cooling in Contemporary Buildings

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Keywords

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Abstract

A passive cooling strategy such as living wall can be applied to reduce the microclimate's temperature. Rumah Turi Surakarta is one of the contemporary hotels that applies living wall in its corridors, to create a cooler microclimate as a response of air temperature increment in Surakarta. This study aims to determine how the performance of the living wall as a passive cooling, by comparing air temperature reduction by living wall elements and sun shading elements. Observations were carried out to retrieve visual and measurement data, then the data were processed using quantitative descriptive methods and comparative analysis. The result showed that several factors that affect living wall's performance as a passive cooling are orientation, the distance of the living walls to the corridor, the distance between plants, and the types of plants. *Krokot Merah* and *Sirih Gading* which are leafier and have a darker leaf color, are capable to reduce the temperature by 0.9°C, while *Lili Paris* which are have a fewer leaf and lighter leaf color are able to reduce by 0.2°C.

1. Introduction

Rapid urbanization and population growth have accelerated the development of residential and commercial buildings, often at the expense of urban green spaces [1], [2], [3] . The reduction of vegetated areas contributes to the urban heat island effect [4], [5], [6] and increases ambient air temperatures at both the macro- and microclimatic scales [7], [8], [9]. Therefore, buildings require greater cooling energy to maintain acceptable thermal conditions, highlighting the importance of passive cooling strategies that can improve outdoor and semi-outdoor thermal environments while reducing energy consumption. Among various passive cooling approaches, vertical greenery systems (VGS), commonly referred to as living walls, have attracted increasing attention due to their ability to reduce solar heat gain, improve microclimatic conditions, and enhance the environmental quality of buildings [10], [11], [12], [13]. Vegetation can lower surrounding temperatures through shading and evapotranspiration while simultaneously improving the aesthetic value of the built environment.

Rumah Turi Hotel in Surakarta, Indonesia, is an award-winning contemporary hotel recognized for its environmentally responsive design. The building received the ASEAN Energy Award 2012 in the Best Tropical Building category for integrating natural elements into its architectural design while promoting energy efficiency [14], [15] . Unlike conventional hotels, Rumah Turi incorporates living walls along the first-floor corridors as a passive cooling strategy to improve the thermal conditions of transitional spaces. In contrast, the second-floor corridors utilize conventional sun-shading devices to reduce direct solar heat gain. Both systems are installed on west- and south-facing façades, providing an opportunity to compare two passive cooling strategies under similar climatic conditions. The building configuration is particularly suitable for comparative field investigations because both corridor types possess similar spatial dimensions, occupancy patterns, and exposure to the surrounding outdoor environment. Consequently, differences in thermal performance can be more directly attributed to the façade treatment rather than to variations in building geometry or operational conditions. This characteristic makes Rumah Turi Hotel an appropriate living laboratory for evaluating passive cooling strategies under real tropical operating conditions.

Although the cooling potential of living walls has been widely reported [10], [11] , limited studies have compared their thermal performance with conventional shading systems in semi-outdoor corridor environments. Furthermore, the influence of design characteristics, such as plant species, plant density, orientation, and spatial configuration, has received relatively little attention in field-based studies. In this case, semi-outdoor corridors represent unique thermal environments because they are simultaneously influenced by outdoor climatic conditions, building geometry, airflow patterns, and façade characteristics [16], [17], [18]. As a result, the thermal mechanisms governing these spaces differ substantially from those of enclosed indoor environments, requiring dedicated field measurements to better understand their cooling performance.

Therefore, this study evaluates and compares the passive cooling performance of living walls and sun-shading devices in Rumah Turi Hotel. Field measurements were conducted to assess key microclimatic variables, including semi-outdoor and outdoor spaces by measuring air temperature, relative humidity, and thermal comfort conditions within the two corridor systems. By comparing the air temperature reduction achieved by living wall elements and conventional sun-shading devices, this study evaluates the passive cooling performance of vegetation-based façade treatment in the semi-outdoor corridors of Rumah Turi Hotel. Furthermore, it examines how design variables, including façade orientation, the distance between the living wall and corridor, plant spacing, and plant species characteristics, influence the cooling effectiveness of the living wall under tropical climatic conditions. The findings are expected to provide practical insights into the design of vegetation-based passive cooling strategies for contemporary buildings in tropical climates.

2. Research Methods

This study employed a descriptive research design using both qualitative and quantitative approaches to evaluate the passive cooling performance of living walls. The qualitative approach consisted of visual observations of the building and vegetation characteristics, while the quantitative approach involved field measurements followed by descriptive and comparative analyses of the thermal data.

2.1 Data Collection

Field observations were conducted to obtain both physical characteristics of the building and environmental measurement data. Building characteristics. Visual observations were carried out to document the architectural features of the building, corridor dimensions, living wall configuration, façade orientation, and plant species used in the living wall system. Photographic documentation was also collected to support the visual analysis.

Environmental measurements. Air temperature and relative humidity were continuously monitored over a seven-day measurement period. Outdoor environmental conditions were recorded using a MISOL Professional Weather Station, which logged air temperature and relative humidity at 5-minute intervals.

Indoor corridor measurements were performed using a MISOL Wireless Weather Station with five sensors (CH1–CH5). The sensors were installed behind the living wall on the first-floor corridor and behind the sun-shading system on the second-floor corridor. Each sensor was suspended approximately 0.90 m above the finished floor level and programmed to record air temperature and relative humidity at 15-minute intervals throughout the measurement period.

The surface temperatures of the living walls were measured using a FLIR Thermal Imaging Camera. Thermal images were captured at four-hour intervals over a 24-hour period to evaluate the thermal response of the vegetation under different environmental conditions.

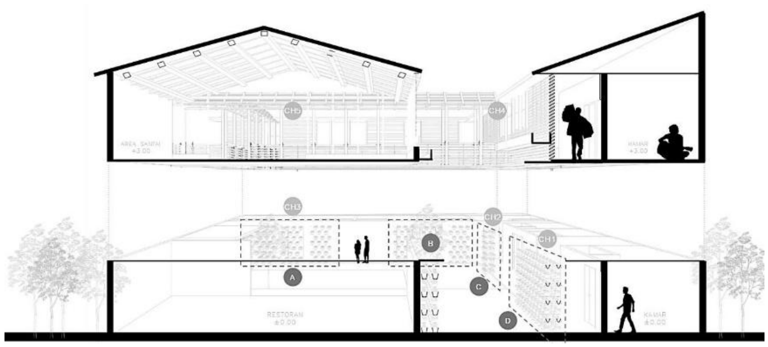


Fig. 1 Locations of the living wall sections (A–D) and the measurement points (CH1–CH5) in the corridor

2.2 Data Analysis

The collected data were analyzed using three complementary approaches: visual analysis, environmental data analysis, and comparative analysis. Visual analysis. Three-dimensional (3D) models of the building were developed using SketchUp and Autodesk Ecotect to examine the building geometry, shading conditions, and solar exposure. The simulation incorporated the building location, local climatic data, orientation, and surrounding context to evaluate the influence of solar movement on the living wall and sun-shading systems throughout the day [19], [20].

Environmental data analysis was conducted using temperature and relative humidity data recorded by the monitoring instruments which were downloaded and processed using Microsoft Excel. The datasets were organized to calculate descriptive statistics, including average values, and to generate graphs illustrating the temporal variations in thermal conditions. The measured environmental conditions were then evaluated against relevant standards and previous studies to assess the thermal performance of the passive cooling strategies.

Comparative analysis involved assessing thermal performance of the living wall and the conventional sun-shading system by comparing the measured air temperature and relative humidity recorded in the semi-outdoor corridors. The comparison was conducted between the first-floor corridor located behind the living wall and the second-floor corridor located behind the wooden sun-shading system. Both measurement locations were selected because they shared the same façade orientation, allowing the influence of the two passive cooling strategies to be evaluated under comparable environmental conditions.

3. Result and Discussion

This section presents the field measurement results obtained from Rumah Turi Hotel and discusses the thermal performance of the living wall system as a passive cooling strategy. The analysis begins with the existing building conditions and the characteristics of the living wall and sun-shading systems, followed by the outdoor environmental conditions during the measurement period. Subsequently, the surface temperatures of the living walls and the thermal conditions within the semi-outdoor corridors are analyzed. Finally, the relationships between the observed thermal performance and the design characteristics of the passive cooling systems are discussed.

3.1 Existing Building Conditions

Rumah Turi Hotel in Surakarta is a two-storey contemporary building with a floor-to-floor height of approximately 3 m. The main building has an L-shaped layout with its principal façade oriented toward the south. As part of its passive design strategy, the building incorporates two different shading systems within its semi-outdoor corridor spaces. Living walls are installed along the first-floor corridors, while wooden sun-shading devices are applied to the second-floor corridors. Both systems are located on west- and south-facing façades, providing comparable environmental conditions for evaluating their cooling performance.

The living walls consist of different plant species and configurations, whereas the sun-shading devices employ a uniform wooden material. The variation in plant characteristics, including species composition and foliage density, provides an opportunity to investigate how vegetation properties influence the thermal performance of the living wall system. The specifications of the living walls and the wooden sun-shading systems are summarized in Tables 1 and 2.

Table 1. Specification of Living Wall

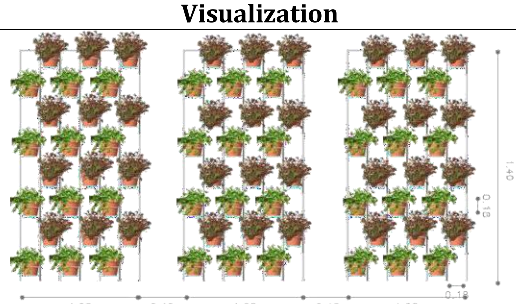
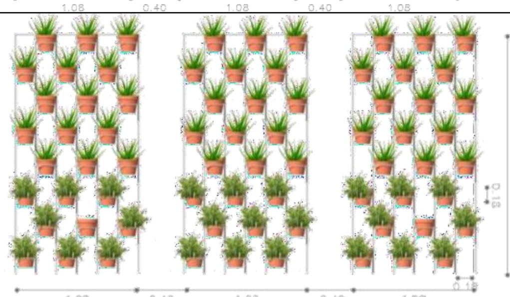
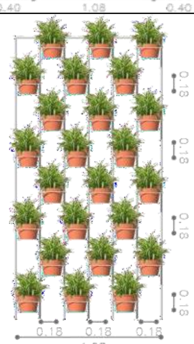
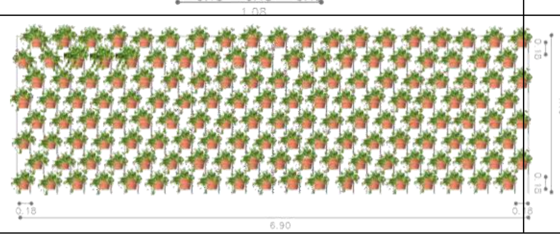
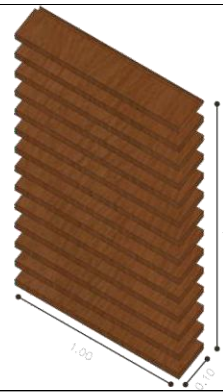
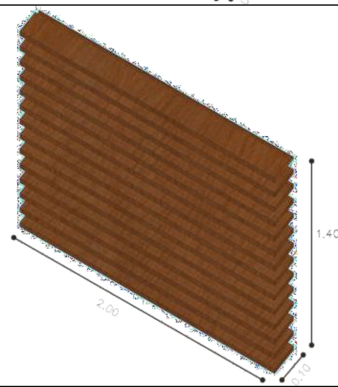
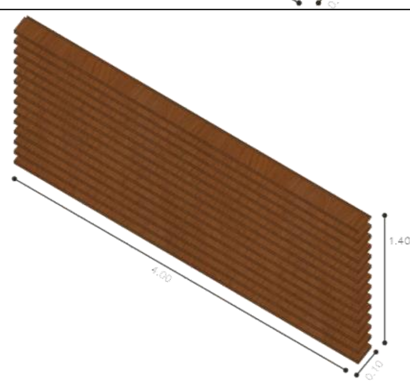
Point	Visualization	Orientation	Plant	Material	CH
A		South	*Portulaca grandiflora (Krokot Merah)* And *Epipremnum aureum (Sirih Gading)*	Clay	CH 3
B		South	*Lidah Buaya* and *Chlorophytum comosum (Lili Paris)*	Clay	-
C		West	*Chlorophytum comosum (Lili Paris)*	Clay	CH 2
D		West	*Epipremnum aureum (Sirih Gading)*	Clay	CH 1

Table 2. Specification of wood Sun Shading

No.	Visualization	Side	Orientation	CH
1		North	South	CH5
2		North	South	-
3		East	West	CH4

3.2 Outdoor Environmental Conditions

The outdoor environmental conditions recorded during the seven-day measurement period provide important context for interpreting the thermal performance of the living wall and sun-shading systems. During the first five days of monitoring, weather conditions were generally characterized by intermittent cloud cover and occasional rainfall, resulting in fluctuating levels of solar irradiance. As expected, periods of clear sky corresponded to increased solar irradiance, whereas cloudy conditions substantially reduced the amount of incoming solar radiation.

The average outdoor air temperature during the measurement period was 28.6°C, with a corresponding average relative humidity of 74.3%. According to previous thermal comfort studies conducted in tropical climates, these environmental conditions indicate a relatively warm and humid outdoor environment.

Figure 2 shows that solar irradiance exhibited a positive relationship with outdoor air temperature and an inverse relationship with relative humidity. As solar irradiance increased, outdoor air temperature also increased because of greater solar heat gain. Conversely, relative humidity decreased during periods of high solar irradiance due to the increase in air temperature. These environmental variations influenced the thermal conditions experienced by the semi-outdoor corridors and therefore provide an essential basis for evaluating the cooling effectiveness of the living wall and sun-shading systems.

Because passive cooling systems rely heavily on surrounding environmental conditions, variations in solar irradiance throughout the measurement period should be considered when interpreting the observed differences in corridor temperature. Consequently, the following analyses compare the thermal responses of the living wall and sun-shading systems under the same outdoor climatic conditions.

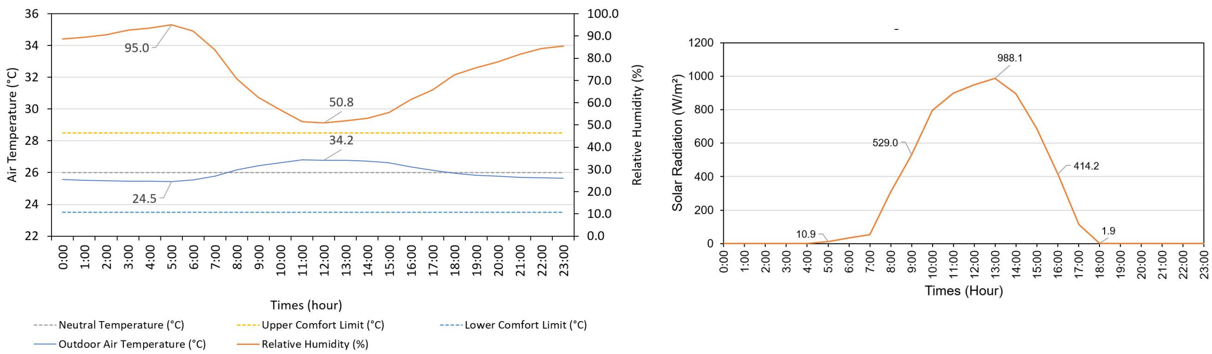


Fig. 2 Average outdoor temperature, humidity and solar radiation

3.3 Surface Temperature of the Living Walls

Surface temperature measurements were conducted on the living walls located at Points A, C, and D, corresponding to the locations where corridor air temperatures were monitored (CH3, CH2, and CH1, respectively). These measurement points were selected to maintain vertical alignment with the monitoring locations installed on the second-floor corridor (CH4 and CH5), allowing a direct comparison between the living wall and the wooden sun-shading systems.

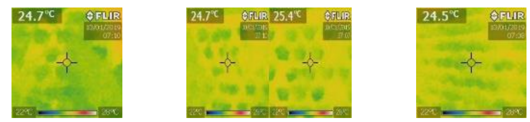
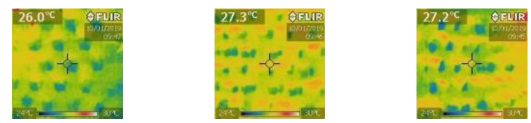
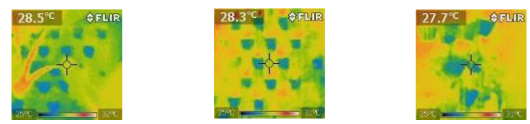
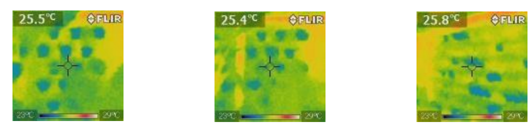
The measured surface temperatures of the living walls are presented in Table 3. Differences in surface temperature were observed among the three living wall configurations throughout the measurement period. Among the monitored locations, Point D consistently exhibited the lowest average surface temperature, whereas Point C recorded the highest surface temperature.

The lower surface temperature observed at Point D is likely associated with the characteristics of Epipremnum aureum (*Sirih Gading*), which forms a dense canopy with relatively high foliage coverage. Dense vegetation provides greater shading of the supporting wall surface and may also enhance evaporative cooling, thereby reducing the surface temperature of the living wall. In contrast, Point C, which was planted with Chlorophytum comosum (*Lili Paris*), consistently exhibited the highest surface temperature. Besides its west-facing orientation, this living wall contained fewer plants with relatively sparse foliage and smaller leaves, resulting in reduced shading effectiveness during periods of high solar exposure.

The observed differences indicate that the thermal performance of living walls is influenced not only by façade orientation but also by vegetation characteristics. Living walls with greater foliage density appear to provide more effective protection against solar heat gain than those with sparse vegetation.

Leaf morphology may also contribute to the observed differences in thermal performance. Living walls planted with Epipremnum aureum (*Sirih Gading*) and Portulaca grandiflora (*Krokot Merah*) generally exhibited lower surface temperatures than those planted with Chlorophytum comosum (*Lili Paris*). Although darker leaf pigmentation may increase the absorption of solar radiation, the present study suggests that the overall cooling performance is more strongly associated with canopy density and vegetation coverage than with leaf color alone. Further investigation is required to isolate the individual influence of these plant characteristics.

Table 3. Living wall surface temperature

Time (WIB, UTC+7)	Existing Living Wall	Measurement Results
06.00	 A C D	 A C D
10.00	 A C D	 A C D
14.00	 A C D	 A C D
18.00	 A C D	 A C D
22.00	 A C D	 A C D

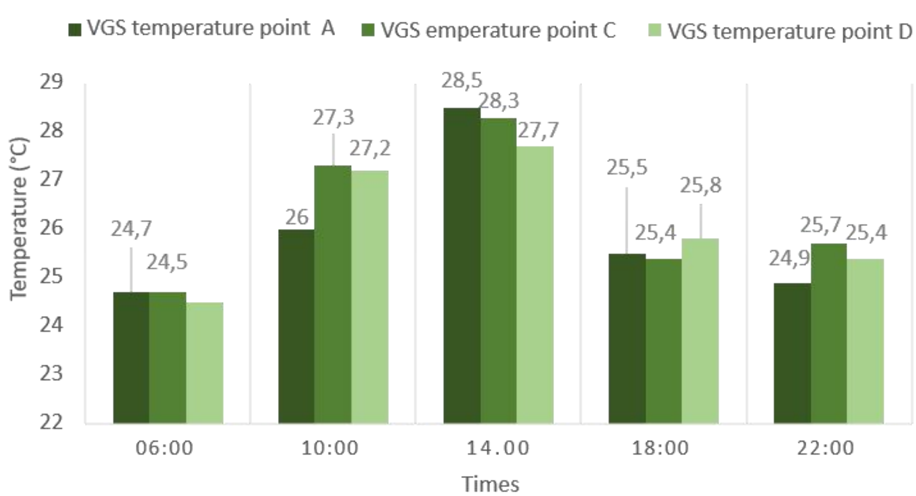


Fig. 3 Living wall surface temperature

3.4 Thermal Conditions of the Semi-Outdoor Corridors

The air temperature measurements indicate that all monitored semi-outdoor corridors maintained lower average temperatures than the corresponding outdoor environment throughout the seven-day observation period, demonstrating the effectiveness of both passive cooling strategies in moderating the corridor microclimate. However, noticeable differences were observed among the monitored locations, indicating that the cooling performance varied according to the characteristics of the passive cooling systems and their environmental exposure.

Among the monitored corridors, CH2, located behind Living Wall C, consistently recorded the highest average air temperature during the measurement period. Unlike the other corridor locations, CH2 reached its maximum temperature at approximately 12:00, whereas the remaining corridors generally reached their peak temperatures at around 16:00. This difference indicates a considerably shorter thermal response time at CH2 compared with the other measurement locations.

The delayed occurrence of the maximum corridor temperature relative to the outdoor environment represents the time lag produced by the building envelope and passive cooling elements. During the measurement period, the outdoor air temperature and solar irradiance simultaneously reached their highest values at approximately 12:00, with an average peak solar irradiance of 532 W/m^2. In contrast, most corridor locations reached their maximum temperatures approximately four hours later, suggesting that the passive cooling systems effectively delayed heat transfer into the semi-outdoor spaces.

The observed time lag varied among the measurement locations. Corridors CH1 and CH3, protected by living walls, together with CH4 and CH5, protected by wooden sun-shading systems, exhibited an average time lag of approximately 4–5 hours. In comparison, CH2 demonstrated a considerably shorter time lag of only 0–1 hour, indicating that this location responded much more rapidly to changes in outdoor climatic conditions.

The relatively limited cooling performance observed at CH2 is likely associated with the combined influence of façade orientation and vegetation characteristics. Living Wall C faces west, resulting in greater exposure to afternoon solar radiation, and is planted with Chlorophytum comosum (Lili Paris), which is characterized by relatively sparse foliage and smaller leaves compared with the vegetation used at the other living wall locations. Consequently, the shading effect provided by the vegetation was reduced, allowing a greater proportion of solar heat to reach the surrounding surfaces and corridor environment.

These findings suggest that the effectiveness of living walls cannot be evaluated solely based on the presence of vegetation. Rather, their cooling performance appears to depend on the interaction between environmental exposure and vegetation characteristics, including façade orientation, canopy density, and plant morphology. This observation provides the basis for the comparative discussion presented in the following section.

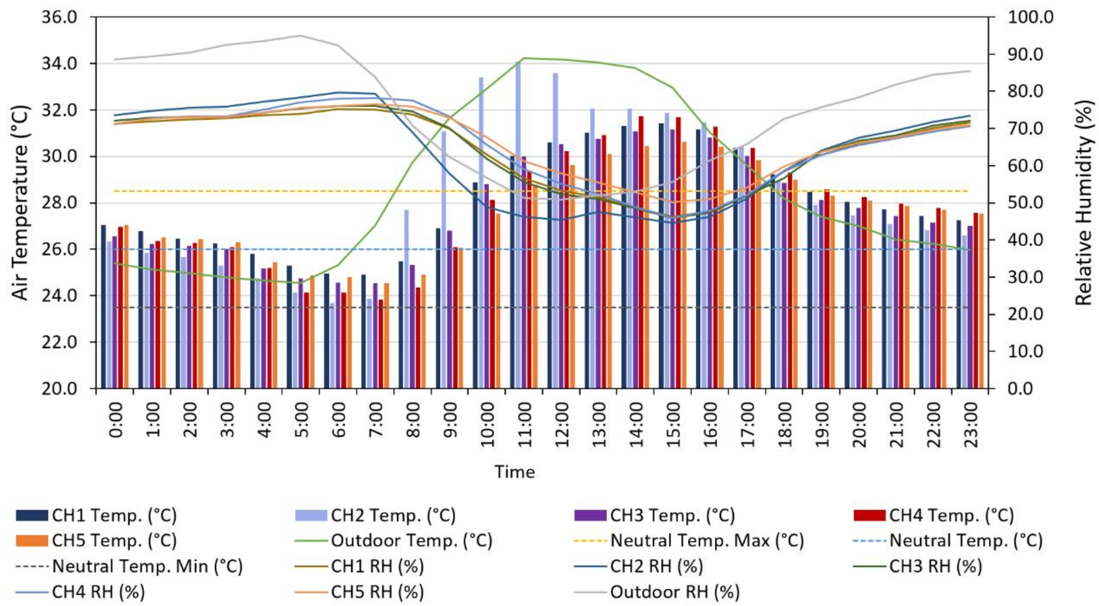


Fig. 4 Average temperature and relative humidity

3.5 Factors Influencing the Thermal Performance of Living Walls

The field measurements indicate that the thermal performance of living walls is influenced by several interrelated design and environmental factors rather than by the presence of vegetation alone. Based on the comparative analysis presented in Table 4, the primary factors affecting the cooling effectiveness of the living wall system include façade orientation, the type of passive cooling element, plant species, vegetation density, and the spatial configuration of the living wall.

Among the investigated factors, façade orientation had a substantial influence on corridor thermal conditions. Living walls installed on west-facing façades were exposed to greater afternoon solar radiation than those facing south, resulting in higher surface and corridor air temperatures. Consequently, the cooling effectiveness of the living wall was reduced under greater solar exposure, particularly when combined with vegetation of relatively low canopy density.

Table 4. Analysis of relationships between variables

Orientation	**Location**	**Shading Element**	**Type / Material**	**Color**	**Outdoor–Corridor Temperature Difference, ΔT (24-hour average)**
South	First Floor *(Living Wall A, sensor CH3)*	Living wall	Portulaca grandiflora (*Krokot Merah*) and Epipremnum aureum (*Sirih Gading*)	Purplish red and dark green	0.90°C
South	Second Floor *(sensor CH5)*	Sun shading	Wood	Dark brown	1.03°C
West	First Floor *(Living Wall C, sensor CH2)*	Living wall	Chlorophytum comosum (*Lili Paris*)	Yellowish green	0.20°C

Orientation	Location	Shading Element	Type / Material	Color	Outdoor–Corridor Temperature Difference, ΔT (24-hour average)
West	Second Floor *(sensor CH4)*	Sun shading	Wood	Dark brown	0.85°C

The comparison between the living wall and the wooden sun-shading system also demonstrated noticeable differences in thermal performance. Under similar façade orientations, the corridors protected by the wooden sun-shading system exhibited greater average air temperature reductions than those protected by the living wall. The wooden shading elements also produced a longer thermal time lag (approximately 4–5 hours), indicating their greater ability to delay heat transfer into the semi-outdoor corridor. This finding suggests that conventional shading devices remain an effective passive cooling strategy, particularly in locations subjected to high solar exposure.

Although the wooden sun-shading system generally produced greater temperature reductions, the thermal performance of the living wall varied considerably according to vegetation characteristics. Living Wall A, planted with Portulaca grandiflora (Krokot Merah) and Epipremnum aureum (Sirih Gading), reduced the corridor air temperature by approximately 0.9°C, whereas Living Wall C, planted with Chlorophytum comosum (Lili Paris), achieved a reduction of only 0.2°C. These results demonstrate that vegetation characteristics play an important role in determining the cooling effectiveness of living walls.

The superior thermal performance observed for Living Wall A is likely associated with the dense foliage produced by Portulaca grandiflora and Epipremnum aureum, which provided more effective shading of the wall surface and surrounding corridor. In contrast, Chlorophytum comosum possesses relatively sparse foliage and smaller leaves, resulting in lower vegetation coverage and reduced protection from direct solar radiation. Greater canopy density may also promote evaporative cooling, further contributing to lower surface temperatures and improved corridor thermal conditions.

The present findings indicate that the effectiveness of living walls should not be evaluated solely by their ability to reduce air temperature. Instead, their thermal performance depends on the combined effects of environmental exposure and vegetation characteristics. Appropriate plant selection, adequate foliage density, and consideration of façade orientation are therefore essential to maximize the passive cooling potential of living walls in tropical buildings.

Overall, this study suggests that the successful application of living walls requires careful design rather than simply incorporating vegetation into the building envelope. Integrating suitable plant species with appropriate spatial configurations can significantly improve the cooling effectiveness of living walls and enhance the thermal quality of semi-outdoor transitional spaces.

4. Conclusions

This study evaluated the thermal performance of living walls as a passive cooling strategy in the semi-outdoor corridors of Rumah Turi Hotel, Surakarta, by comparing their cooling effectiveness with that of conventional wooden sun-shading systems. The field measurements demonstrated that both passive cooling strategies contributed to reducing corridor air temperatures compared with the outdoor environment; however, their cooling performance varied according to their design characteristics and environmental exposure.

Among the investigated living walls, vegetation composed of Portulaca grandiflora (Krokot Merah) and Epipremnum aureum (Sirih Gading) achieved the greatest air temperature reduction (approximately 0.9°C), whereas Chlorophytum comosum (Lili Paris) produced a considerably smaller reduction (approximately 0.2°C). The observed differences are likely associated with variations in façade orientation, vegetation density, plant morphology, and the spatial configuration of the living wall system.

The results indicate that the thermal performance of living walls is governed by the combined influence of façade orientation and vegetation characteristics rather than by the presence of vegetation alone. Living walls with denser canopy coverage and appropriate plant selection exhibited greater cooling effectiveness and produced more favourable thermal conditions within the semi-outdoor corridors. The findings of this study provide practical guidance for the design of vegetation-based passive cooling systems in tropical buildings. When implementing living walls, designers should consider not only the selection of plant species but also façade orientation, vegetation density, and spatial arrangement to maximize cooling performance.

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