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EFFECTIVENESS OF MODULAR LIVING WALL SYSTEM FOR HEAT REDUCTION: A CASE STUDY OF AN URBAN TRANSFORMATION CENTER IN PASIR GUDANG

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ABSTRACT

In urban areas, humans' thermal comfort is a crucial concern related to the Sustainable Development Goals (SDGs). Living wall system (LWS) can be used as a climate mitigation measure to improve temperature at an outdoor building. Studies on LWS' thermal performance of plant species are still scarce, especially for tropical countries. As such, this study aimed to investigate the cooling potential of vegetation with specific plant characteristics. An experimental study of the LWS was undertaken in the industrial city of Pasir Gudang, Malaysia. Four plant species, Philodendron burle-marxii, Phyllanthus cochinchinensis, Nephrolepis exaltata and Cordyline fructicosa 'Miniature', were evaluated in 4-metre (width) x 1-metre (height) of LWS. The study was carried out continuously for three months, from January until March 2019. The data were then analyzed using IBM SPSS Statistic 24. The findings revealed that Philodendron burle-marxii demonstrated the best cooling capacity among the tested plants as it caused its surrounding temperature to be 2.85 oC during the daytime. It was shown that the broader leaves and higher leaf area index value of the species gave a good response to air temperature reduction in the outdoor environment. Meanwhile, Phyllanthus cochinchinensis was the most efficient species as it obtained the highest reduction of surface temperature with an average of 6.17 oC. This study also confirmed that dense branching and multi-stemmed *plants influence the lowering of surface temperature with a smaller leaf and higher leaf area index value. In brief, the combination of a higher leaf area index with several plant morphology is recommended for temperature reduction through the different abilities of plant species.*

Keywords: *Green infrastructure, Living wall system, Thermal effects, Plant morphology*

INTRODUCTION

The concept of urban green infrastructure (G.I.) has been defined as a set of man-made elements that provide multiple ecosystem services at the building on an urban scale (Coma et al., 2017). Even though G.I. provides various goods and benefits environmentally and socially, the study of G.I. in developing countries in Southeast Asia and Africa requires greater attention (Seng et al., 2022). In general, G.I. is a multi-functional approach that conserves and rehabilitates natural resources, removing harmful threats, reconnecting habits, and reducing the depletion of ecosystem services for sustainable growth of a city or town (Hepcan, 2013; Gasparovich et al., 2017; Vieira Mejía et al., 2015; Lee and Oh, 2019). G.I. also promotes recreational and tourism opportunities, creates better health, and promotes urban dwellers' well-being and quality of life (Demir, 2019; Zuniga-Teran et al., 2020). It is important to note that the physical features contributing to G.I. include parks, gardens, green roofs, vertical greenery systems, streams, restored brownfields, and coastal and dunes (Pérez et al., 2016). This research investigates mitigating the urban heat island effect in the urban environment in Malaysian cities. Vertical greenery systems, like other forms of G.I. are increasingly being considered a design feature to solve the current problems of the developed urban environment.

Urbanization has induced change in land use/land cover (LULC), contributing to the rise of urban temperature and heat intensity. These changes have contributed to thermal discomfort, heat stroke, hyperthermia, and even death cases (Yeo et al., 2021). According to Basher et al. (2016), a vertical greenery system (VGS) acts as a passive cooling agent, protecting the facade against direct solar radiation and reducing the buildings' temperature. It is being suggested as one of the urban greening technologies, especially for hot cities, to improve urban climates. The trend of VGS is becoming popular due to the benefits they offer throughout the year. Since 1988 (Hoyano, 1988), more than 127 studies published in the scientific literature on VGS have significantly increased annually. Nonetheless, the number of studies on LWS is relatively small compared to VGS types of urban greenery.

There is little attention given to the effectiveness of LWS in offering an effective thermal performance in tropical climates, especially in industrial cities. Previous studies have been based on experimentation from existing vertical greenery (Jaafar et al., 2011; Galagoda et al., 2018) and simulation (Wong et al., 2009; Shafiee et al., 2020) studies. The initial scientific interest in LWS has attracted the attention of researchers and industries since 2009. In a tropical country, the thermal benefits of LWS have been investigated through experimental studies such as Thailand (Charoenkit and Yiemwattana, 2017), Singapore (Wong et al., 2010), Indonesia (Widiastuti et al., 2018), and Malaysia (Safikhani et al., 2014). Their findings have demonstrated the capability of greenery to reduce temperatures in different settings. The relationship between thermal performance and plant character using LWS in Malaysia has not received sufficient attention. These are among the variables that should be adequately considered to achieve temperature reduction. There are few studies related to LWS, the comparison of the system (e.g., Jaafar et al., 2015), and the air gap from the greenery (e.g., Safikhani and Baharvand, 2017), but none of the studies investigated LWS plant types. This means that studies on the LWS thermal performance of plant species are still scarce, especially in industrial cities.

LITERATURE REVIEW

Type of Vertical Greenery System

Vertical greenery system (VGS) has two main approaches: the green façade system (GFS) and the living wall system (LWS) (Jaafar et al., 2013; Bustami et al., 2019; Abd-Ghafar et al., 2023). Generally, the green facade system is known as a ground-based system, while the living wall system is recognized as a wall-based system. The four types of green façade are double-skin green façade, traditional green façade, double-skin green façade with planter boxes (Jaafar, 2015; Perini et al., 2011), and perimeter flowerpots (Wang et al., 2016; Wilmers, 1990). This illustrates the possible presence or absence of a supporting structure for climbers. The support structure has two benefits: to prevent the vegetation from falling and to create an air gap between the surface of the building and the vegetation. Meanwhile, the LWS is an advanced technology of VGS. Unlike GFS, which relies on climbing or hanging plants that can be attached, an LWS is equipped with an irrigation system and a medium for growth. The classification of LWS suggested by Manso and Castro-Gomes (2015), Charoenkit and Yiemwattana (2016), and Cuce (2017) indicate there are two main types of LWS: continuous and modular. However, according to Medl et al. (2017b), there is an additional type, namely, a landscape wall.

There are several reasons why the modular LWS was selected in the experimentation rather than a GFS. First, LWS provides a variety of plant pallets, has options for replacing unhealthy plants (Charoenkit and Yiemwattana, 2016), and is suitable to be applied to high-rise buildings. These reasons illustrate that the application of the module system is more effective to maintain compared to other systems. A variety of plant species is used, and the building is visually pleasing (Othman et al., 2018). Second, an LWS uses soil and a lightweight growing medium with greater depth for plants to be rooted in compared to fabric felt layers or panel systems. Then, an LWS has better heat reduction and increases the relative humidity of its surroundings. It is in line with Jaafar (2015) that the LWS provides more benefits than the GFS. This technology seems to be the most appropriate for the tropical climate in Malaysia.

Plant Morphology

In plant selection, it is essential to consider the plant morphology, plant medium (López-Rodríguez et al., 2016), water system, and wall coverage area (Perini, Bazzocchi et al., 2017). Plant morphology is the element of plant physiology that describes the structure of plants. It includes several criteria; leaf area index, size and characteristic of plant species, to identify the type of plants.

Leaf Area Index and Coverage Area

Watson (1947) defined the Leaf Area Index (LAI) as the total leaf area of all leaves of a plant per unit ground surface area. With trees, researchers generally use the ground surface area to represent the canopy of a tree. Meanwhile, the LAI for shrubs is divided over the shrub bed (Tan and Sia, 2010). LAI is also known as the leaf density or the leaf mass of canopy structures. According to Pérez et al. (2017), LAI value depends on the plant's type and growth phase, it ranges from 0 to 10. It is an essential variable in plant physiology because it indicates the relation between leaf density and the shadow effect (Wong et al., 2010; Jaafar et al., 2015; Abd-Ghafar et al., 2020), thus determining the overall cooling effect (Koyama et al., 2013). Plants with high coverage and thicker canopies are more efficient in cooling a building as a passive energy tool (Pérez et al., 2017). It means that the LAI has influenced the thermal impact by controlling the light that passes through the canopy into the ground area and resulted in the cooling effect. A review study by Charoenkit and Yiemwattana (2016) stated that plants with four or more LAI values are preferred in LWS because of energy savings, while plants with an LAI below two should be avoided. For instance, Wong et al. (2009) investigated a simulation of several plant species, of which Nephrolepis exaltata had an LAI of 6.76, which has a high potential to reduce temperature.

Leaf Characteristics and Size

The leaf size can ameliorate heat performance depending on the LAI (Mat Sulaiman et al., 2018). White and Montes-R. (2005) postulates that broader leaves can absorb more light and enhance the cooling effect. So, the leaves can contribute to a higher percentage of coverage from vertical planting. However, Charoenkit and Yiemwattana's (2017) study indicates otherwise; smaller leaf size and a higher LAI value resulted in higher temperature reduction. Meanwhile, Taib et al. (2019) found that a multi-stemmed plant provides multiple layers of shading, thus more effective in radiation filtration. Due to the inconsistency of findings on leaf characteristics influencing the thermal performance of a building, this study would also consider these parameters in the experimentation.

METHODOLOGY

Location of the Study

Pasir Gudang is in Mukim Plentong at Johor Bahru, Malaysia. It is one of the large leading industrial areas located between latitude 1° 30'10"N and 103° 56'8" E with a total area of approximately 359.6 km2. Pasir Gudang has an average mean temperature of 33.21 oC and 86.53% relative humidity (Department of Environment, 2016). The experiment site is located on an Urban Transformation Center (UTC) wall in Pasir Gudang. UTC is one of the government's initiatives to provide various key government and private sector services under one roof for the urban community. Pasir Gudang is surrounded by industrial activities such as shipbuilding, transportation and logistics, petrochemicals, distribution and oil palm storage located in Tanjung Langsat Port and Johor Port, and other heavy industries (see Figure 1). Given their nature, these industries emit a large amount of heat (Dahiru and Hashim, 2020). As a result, high temperatures from these activities may pose a severe risk to the city residents. Therefore, mitigating industrial heat through living wall systems might be feasible to reduce heat radiated from the sun and industrial zone.

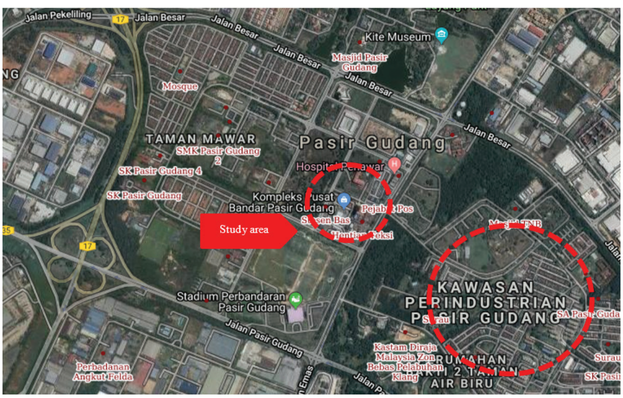

Figure 1. UTC Building in Pasir Gudang that Faces the Industrial Area in a Radius of 10 km

Source: Author

Installation of Living Wall System

The LWS was installed facing the industrial area in a radius of 10 km, as shown in Figure 1. This study has adapted the experimental scale of 1m2 for each plant species. Small-scale experimentation was also used in tropical climate studies (Mat Sulaiman et al., 2018; Safikhani and Baharvand, 2017). This type of modular living wall called the Advance Hook-on Green Module System (refer to Figure 2), was suitable for low-height installation. These modular living walls were hooked onto the wire-mesh base to allow easy installation and maintenance.

Figure 2. Experimental study at the wall of UTC building in Pasir Gudang
Source: Author

Plant Selection

The LWS was installed facing the industrial area in a radius of 10 km, as shown in Figure 1. This study has adapted the experimental scale of 1m2 for each plant species. Small-scale experimentation was also used in tropical climate studies (Mat Sulaiman et al., 2018; Safikhani and Baharvand, 2017). This type of modular living wall called the Advance Hook-on Green Module System (refer to Figure 2), was suitable for low-height installation. These modular living walls were hooked onto the wire-mesh base to allow easy installation and maintenance.

Table 1. Criteria of Plant Species Selected in this Study

Plant species	*Philodendron burle-marxii*	*Phyllanthus cochinchinensis*	*Nephrolepis exaltata*	*Cordyline fructicosa 'Miniature'*
Suitable to hot and humid conditions				
Weather tolerance	Semi-shade, semi-hardy	Full sun, hardy plant	Semi-shade, semi-hardy	Full sun, hardy plant
Maintenance	Medium	Low	Medium	Low
Leaf size	Large (broad leaf)	Small	Medium	Medium
Growth pattern	Vine and spreading	Dense branching, multi-stemmed plant	Lush leaves	The cluster at the tip
Leaf Area Index (LAI)	5.13	5.22	5.38	3.72

Plant selection for this experiment was based on six criteria, as shown in Table 1. The criteria include 1) suitability to hot and humid conditions, 2) classification of leaf size- small (1-3 cm length), medium (4-10 cm length), and large (more than 10 cm length), 3) maintenance of the plant, 4) growth pattern, 5) weather tolerance, and 6) leaf area index (Charoenkit and Yiemwattana, 2017; Mat Sulaiman et al., 2018).

Figure 3. Four Species of Plants were used in the Experiment
Source: Author

Leaf Area Index (LAI) can be measured by using two methods. The direct methods involve harvesting random leaves from a plot. It is suitable for vegetation in small structures (Bréda, 2003; Abd-Ghafar et al., 2020). In contrast, indirect methods measure variables using technological equipment such as Plant Canopy Analyser LAI-2200 (LI-COR Biosciences, Lincoln, USA), a practical tool used for indirect measurement, but it is relatively costly. Therefore, the direct LAI measuring method is preferred in this study. The LAI measurement was adapted from Charoenkit and Yiemwattana (2017), which used the ground base as the potted area for various plant species. The branching and growth patterns that affect the radiation absorbed by the plants were also observed (Taib et al., 2019). The following species were selected to use in the experimentation: Philodendron burle-marxii, Phyllanthus cochinchinensis, Nephrolepis exaltata, and Cordyline fructicosa 'Miniature' as shown in Figure 3. The plants are also the common species that grow well in Malaysia's tropical climate but have not yet been thoroughly examined in previous research. All the plants were grown in a substrate sold in the local market for general ornamental planting purposes.

From this study, forty-two plants for each species were planted in an LWS measuring 1 m2. The plant materials were grown with a minimum 85% growth rate at Chop Ching Hin Nursery, Johor Bahru, for three months. They were transplanted to the site to adapt to the new environment on the building façade before the measurements were taken.

Data Collection and Analysis

Sample acquisition was carried out from 12:00 pm of January 1, 2019 until 12:00 pm of April 1, 2019, daytime from 07:31 to 19:30 local time and night-time from 19:31 to 07:30. The data logger of air temperature was suspended at the middle of the height of each plant species and covered by a reflective cover (aluminium layer to protect the sensors against solar radiation) at a distance of 30 cm from the concrete wall (Wong et al., 2010). Both the greenery of each plant species and the bare wall were recorded for air temperature and relative humidity by HOBO UX 100-011 Temp\RH Data Logger, which only has a single channel. Besides that, HOBO UX 120-006M 4-Channel Analog Logger with four cable connection channels was used to measure the surface temperature, as tabulated in Table 3. Thus, this study used two data loggers to set up five measurements, as four cables were connected to the LWS and one to the bare wall to take measurements at 30-minute intervals for 24 hours a day. These cables, called AVS sensors, were connected to the HOBO and fixed onto the wall surfaces with masking tape. A total of 5,812 items of data were collected over the three months of the study from January to April 2019 for each variable. This means there was a total of 11, 624 items of data collected for the two thermal variables, namely, surface temperature and air temperature of each species.

All the data transferred from HOBOware Pro software were then exported into an M.S. Excel spreadsheet (Onset Computer, 2012). The data were then evaluated from 9:00 am to 7:00 pm because the temperature patterns started showing a remarkable temperature reduction, as demonstrated in Figure 4.

Table 2. Equipment used in the Thermal Assessment

Variables	Name of equipment	Number	Range of data collected
Air temperature	HOBO UX 100-011 UX 100 Temp\RH Data Logger (Onset, USA)	4	Fitted for 3 months (January-March) 1 Point- each species and control variable at a bare wall
	Hoboware Pro Software	1	
Surface Temperature	HOBO UX 120-006M 4 Channel Analog Logger	1	Fitted for 3 months (January-March) 1 Point- each species and control variable at a bare wall
	Attached with AVS Sensor (TM C50-HA)	4	
	Hoboware Pro Software	1	

Source: Author

The analysis of this study involves comparing the data between five groups, four from the plant species and one from the bare wall. The data was then run using one-way ANOVA and post-hoc analysis. These analyses used IBM SPSS Statistics 21 to validate the data through significant values, p-value< 0.05. This analysis method is used to measure the group's difference and identify the significant value.

RESULTS AND DISCUSSION

This analysis portrayed the thermal effect of the LWS in the industrial city of Pasir Gudang, Johor. The two variables measured in this field study were air temperature and surface temperature (Widiastuti et al., 2018; Safikhani and Baharvand, 2017; Wong et al., 2010). The bare wall was also considered without any greenery in front of the white-painted concrete wall. This is because heat absorption can be affected by the colours. Similarly, Tan et al. (2014) found 35% less heat on white walls than on the black surfaces of the greenery. Hence, this study fixed the LWS on the white building façade to determine its cooling effect.

Air Temperature Distribution

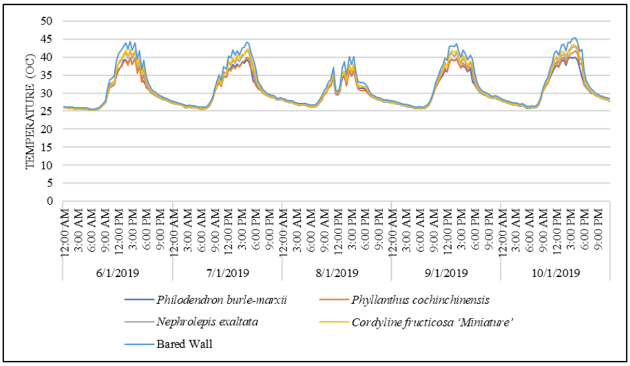

Figure 4. Comparison of Air Temperature among Four Plant Species

The analysis results from ANOVA showed a statistically significant difference in the mean air temperature distribution between four plant species and a bare wall, where $F\ (4, 9110) = 176.201$, $p = 0.000$). Figure 4 shows the diurnal variation of all plant species and bare wall. The results suggest Philodendron burle-marxii, Phyllanthus cochinchinensis, and Nephrolepis exaltata have shown great potential in air temperature reduction while Cordyline fructicosa' Miniature only affords a slight air temperature reduction. The results presented Philodendron burle-marxii had the highest average temperature reduction with a difference of 2.85 oC. The average air temperature was then followed by Phyllanthus cochinchinensis and Nephrolepis exaltata, with differences of 2.59 oC and 2.51 oC, respectively. However, Cordyline fructicosa 'Miniature' revealed the minimum reduction in average air temperature of 0.97 oC, which is below 1 oC.

Surface Temperature Distribution

The LWS plants' surface temperatures were directly exposed to the sun to determine the surface temperature reduction due to the four plant species compared with a bare wall. It had the benefit of lowering the energy demand for cooling building interiors. The data were also run using one-way ANOVA and post-hoc analysis for the three months. The one-way ANOVA analysis shows that the significant p-value was 0.000, below 0.05. Therefore, there was a statistically significant difference in the overall analysis of the mean surface temperature effect between the four plant species compared to a bare wall. The value was $F(4, 9110) = 2731.609$, $p = 0.000$ ($p < 0.05$).

There was a statistically significant difference in the surface temperature effect between the bare wall and all plants, where all the p-values were below 0.05. The analysis showed that Phyllanthus cochinnensis was the best performer among the four tested plant species. The reduction obtained when compared to the bare wall was 6.17 oC. Besides that, Philodendron burle-marxii was the second-highest performer, with a reduction of 5.67 oC. Then, it was followed by Nephrolepis exaltata, the third-highest reduction in mean surface temperature at 5.49 oC. The least effective plant species was Cordyline fructicosa' Miniature' with 4.97 oC. Therefore, the best plant species in ranking on surface temperature pattern were Phyllanthus cochinchinensis, then Philodendron burle-marxii, followed by Nephrolepis exaltata. Cordyline fructicosa' Miniature demonstrated had the lowest surface temperature reduction at the outdoor building of Pasir Gudang.

Discussion of Air Temperature

Figure 5 shows the results of air temperature in the LWS study. The air temperature range examined was between 0.97 °C and 2.85 °C from the four plant species. This study illustrated a similar air temperature pattern to Widiastuti et al. (2018) from Indonesia, the air temperature was reduced from 1.20 °C up to 3.00 °C. In contrast, Safikhani and Baharvand (2017) obtained a reduction in air temperature lower than 1.5 oC. It is noticeable that their research showed a lower average air temperature reduction than the present study. This is because this study has been investigated longer than the aforementioned study. Thus, there was a significant effect on air temperature reduction, demonstrating the findings' validity from the long study period.

Three species that illustrated an excellent performance for average air temperature were Philodendron burle-marxii, Phyllanthus cochinchinensis, and Nephrolepis exaltata. These species have larger LAI values which are more than the 4 value, as stated in Table 2. Similar to Charoenkit and Yiemwattana (2016) showed that four or more LAI values are preferred in the LWS because of their contribution to cooling capacity. LAI becomes the variable for cooling capacity in the LWS to represent the leaf density. Meanwhile, Cordyline fructicosa' Miniature' was the poorest for average air temperature reduction among the four tested plant species. It possessed the lowest reduction every month, resulting in the lowest average differences. The average air temperature was reduced by 0.97 °C for three months, less than 1 oC compared to the bare wall. These findings showed the least significant effect between the LAI value and air temperature reduction. It had the mean LAI value was 3.72. This species showed the leaves were not as dense as Philodendron burle-marxii, Phyllanthus cochinchinensis, and Nephrolepis exaltata. The least dense leaves reduced the potential evapotranspiration and provided a lower air temperature for the Pasir Gudang outdoor building. The smaller LAI value of Cordyline fructicosa' Miniature' resulted in a minimum reduction in the air temperature. Therefore, it shows that the LAI value strongly correlates with the air temperature reduction from the LWS.

Leaf size was identified as another factor affecting the thermal performance of the LWS after the LAI value. The leaf sizes were classified into three large groups (> 10 cm) for Philodendron burle-marxii; medium (4-10 cm) for Phyllanthus cochinchinensis and Nephrolepis exaltata, and Cordyline fructicosa' Miniature' categorized in small leaf (1-4 cm). The wider leaf of Philodendron burle-marxii has obtained a higher average air temperature difference. This species also illustrated that the higher LAI value and wider leaf size performed the best cooler for air temperature reduction, 2.85 °C. It is consonant with a study by Mat Sulaiman et al. (2018) that larger leaf sizes contributed to higher cooling effects. Large leaves seemed advantageous in terms of shade provision of air temperature. Thus, this study found that leaf size was another key variable indicating the cooling capacity.

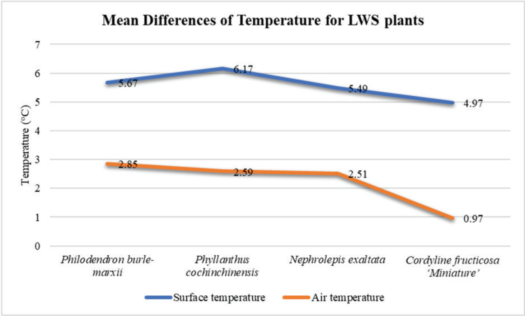

Figure 5. Comparison of Air Temperature and Surface Temperature among Four Plant Species

Source: Author

Phyllanthus cochinchinensis reported second higher average temperatures, 2.59 °C, with a higher LAI value but the smallest leaf size. This study shows that Nephrolepis exaltata had a very similar finding to Phyllanthus cochinchinensis for average air temperature, 2.51 °C. This species was found to have a higher LAI value with medium-sized leaves. Contrastingly, the medium leaf size with the lowest LAI value for Cordyline fructicosa 'Miniature' performed worst in ameliorating the air temperature. Empirically, these four plant species from the LWS demonstrated their effectiveness in lowering the air temperature compared to the bare wall. Philodendron burle-marxii played a pivotal role in air temperature difference; higher LAI value with larger leaf size significantly reduced the air temperature in the site study. It presented that air temperature reduction from LWS has a strong relationship with plant morphology (Perini et al., 2017).

Discussion of surface temperature

Table 2 tabulates the leaf character influenced the surface temperature of LWS. The finding of the surface temperature was contrasted with the air temperature. Phyllanthus cochinchinensis has the highest LAI value of 5.22, with the smallest leaf size reduced, 6.17 oC. Shade leaves also were held at various angles depending on the degree and morphology of the species (McMillen and McClendon, 1979). It means that the growth pattern of Phyllanthus cochinchinensis, being dense branching, allows greater radiation filtration. Multiple layers of this plant offer convincing evidence with an increasing LAI value throughout the study. This species is classified as a multi-stemmed plant, which serves a dropping pattern. As Shahidan et al. (2010) suggested, a high branching density helps to block radiation from reaching the ground. In other words, the ground of vertical planting was referred to as the building façade, which was behind the greenery. Therefore, the sunlight was reflected or blocked from arriving at the wall.

The second-best performer of surface temperature was Philodendron burle-marxii, 5.67 oC with an LAI value of 5.13. This species was not as dense as Phyllanthus cochinchinensis due to its vine and spreading growth habit. Nephrolepis exaltata had an average surface temperature reduction of 5.49 oC. It has a medium leaf size and the highest value of LAI with 5.38. Meanwhile, Cordyline fructicosa' Miniature' had the least effective performance regarding surface temperature reduction among the four plant species. This plant species has a medium leaf size, and the pattern of growth habit showed a cluster of elongated leaves at the tip. This species had the smallest LAI value 3.72 compared to other species. As the plant matures, the leaves become less visible at the plant's bottom. This is because the plants' maturity positively contributed to the shading effect (Charoenkit and Yiemwattana, 2016), represented by the LAI value. Thus, it filtered sunlight penetrating the facade of the building.

Surface temperature reduction through the LWS creates a much cooler building wall surface resulting from heat absorbance, scattering of incident solar radiation, and evapotranspiration (Pérez et al., 2014) by plant species. All four plant species illustrated the significant differences compared to a bare wall. This empirical study has been effective in cooling performance of surface temperature reduction of 6.17 oC from the small-scale study, which is in line with the findings of Charoenkit and Yiemwattana (2017) that showed a reduction of up to 7.2 oC. It indicates that a small-scale study was competent in reducing higher surface temperature differences. The reduction in the surface temperature leads to a lower cooling load for the building interior to alter the microclimatic conditions (Perini et al., 2011). Appropriate plant selection has been investigated and is cooler than a conventional building façade. Therefore, this study has found that plants with a high LAI value due to the small leaf size and dense branching were the most suitable species to achieve the combined effects of the building façade, specifically at Pasir Gudang.

CONCLUSION

This study experimented with the thermal effects of LWS with the planter in a tropical climate. The comparison to the bare wall without plants demonstrates the cooling capacity of LWS. The study illustrated the relationship between plant morphology and climatic variables in LWS. The best performer for air temperature reduction was Philodendron burle-marxii, influenced by plants having broad leaves and a higher LAI value. However, the effects of surface temperature reduction were contradicted. Phyllanthus cochinchinensis was shown to have the most significant effect in reducing surface temperature. Despite the higher LAI value, it has the characteristics of having dense branching and being multi-stemmed. Likewise, the second most effective plant that improved the surface temperature was Philodendron burle-marxii. Amongst the four plant species evaluated from the LWS, Cordyline fructicosa' Miniature was the plant species that achieved the lowest reduction in air temperature and surface temperature. This species was found to have the lowest LAI value and has fewer leaves upon its maturity. To optimize the thermal performance of LWS, plants with higher LAI and larger leaf sizes are suited for air temperature reduction. Meanwhile, higher LAI, small leaf size, and appropriate plant growth pattern should be selected to give cooling capacity for building the façade. The findings of this study are of practical significance, as they can guide practitioners and policymakers, such as landscape architects, urban planners and designers, and environmental engineers, in improving human thermal experiences and promoting a more livable and sustainable industrial environment.

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AUTHOR CONTRIBUTIONS

All authors contributed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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