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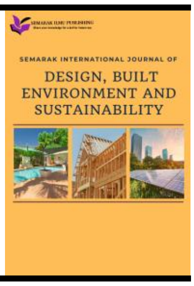

Exploring the Effectiveness of Green Wall and Roof Retrofitting Practices in Brunei Darussalam

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ABSTRACT

Brunei Darussalam faces sustainable challenges related to energy efficiency and environmental quality. These issues can be tackled through the implementation of bioclimatic strategies into building design and construction. Green wall and roof in buildings aimed to reduce the indoor air temperature without excessive use of mechanical cooling systems. This research aims to quantify and confirm the effectiveness of green wall and roof systems in reducing the indoor temperatures with buildings in Brunei emphasizing their contribution to sustainable environment within the local context. Results revealed that both green wall and roof showed significant reduction of indoor temperature during peak daytime periods. The green wall experiment has shown 3.5°C maximum indoor temperature reduction while green roof experiment has shown 5.4°C, both during peak daytime hours, showing maximum temperature decrease of 9.1% and 13% respectively. The indoor temperature reduction was proved to be inadequate to reach optimum comfort for building occupants and to fully eliminate the use of air conditioners. The study suggested that green infrastructure alone cannot fully mitigate the use of mechanical cooling systems, but still be able to reduce their usage. This can still lead to slight energy savings and improved energy efficiency in buildings. Green wall and roof have the potential to enhance thermal comfort and biophilic benefits in buildings, creating more pleasant indoor environments for occupants. In general, the findings of these experiments emphasize the possibility of green wall and roof as a versatile answer for enhancing indoor spaces, advancing sustainability, and improving the well-being in buildings.

1. Introduction
1.1 Background

There have been significant steps taken by Brunei in the direction of sustainable development. In order for Brunei to achieve its national vision, Brunei Vision 2035, it must become a highly educated and prosperous nation [1]. Bioclimatic strategies have been identified as a method of achieving climate adaptability by Košir [2]. In places with high electricity price to gross domestic product

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(EPGDP) ratios, bioclimatic strategies are especially cost-effective. There is potential to save up to 34%, 60% and 61% of energy in warm, moderate, and cold climates, respectively [3]. Whenever energy is affordable, bioclimatic design can be beneficial to the environment.

1.2 Problem Statement

According to the International Energy Agency (IEA), about 36 percent of the planet's energy are being consumed mainly by the building and construction sector alone and contributed about 39 percent towards the production of carbon dioxide emissions in the world [4]. Resources in Brunei Darussalam, especially oil and gas, are currently limited and might not even last for few more decades. Due to this, it is crucial for the building sector around the world to transition towards sustainability to drastically reduce the effects of climate change.

Based on the findings from United Nations, the largest contributor to global greenhouse gas emission is the energy supply sector accountable for around 35 percent. It is also stated that over half of all electricity is consumed by residential and commercial building. It is also mentioned by the United Nations that current lifestyles are unsustainable where resources such as fossil fuel, to generate energy, have been burned more than tripled for its extraction and the number continues to grow. This rapid burning of resource causes the gases in earth's atmosphere trapping the heat of the sun causing the greenhouse effect [5]. Not only resulting in climate change, but natural resources are also rapidly depleted if the same lifestyle is maintained.

Brunei experiences hot, humid, and rainy weather all year round due to its equatorial climate. Bandar Seri Begawan, the capital city of Brunei, has an average temperature of 27°C [6]. From April to August, temperatures can sometimes reach 35°C to 36°C. Nights remain warm, never dropping below 20°C.

Houses in the warm and humid climate mostly experiences high indoor temperatures where building occupants heavily relies on air conditioning which often leads to high energy consumption in every dwelling. High energy consumption means more costly energy bills, which directly affect the building occupant's living expenses leading to a poor living standard in Brunei.

Studying bioclimatic strategies to decrease temperature and comfort in hot and humid areas, particularly natural ventilation, is crucial for sustainable building design and retrofitting. This research can guide decision-making toward more sustainable approaches, like prioritizing natural ventilation over high-energy cooling systems, to reduce energy consumption by up to 32%, making it the best approach for reducing greenhouse gas emissions while assessing feasibility and social acceptability [7-9]. Enhancing indoor environmental quality and occupant comfort can improve health and well-being in hot and humid climates, supporting a sustainable built environment that addresses climate change and urbanization challenges [10-12]

1.3 Literature Review

Mechanical air conditioning is often favoured as the primary cooling solution in the hot and humid regions. Brunei is no stranger to this culture and is already experiencing high electrical loads due to the overuse of air conditioning. Human perception of comfort is dependent on the balance between the air temperature and mean radiant temperature. Cooler surfaces often lead to a more comfortable experience in the hot and humid regions. From this knowledge, it can be summarized that radiant heat are affected by shading designs, insulation, and choice of materials of the building surface. The broader range of accepted "comfortable" temperature in the hot and humid region was discovered as between 25°C to 31.6°C [13]. Residential building occupants are able to tolerate temperature as near as 30°C, suggesting a comfort temperature range between 28°C and 32°C [14].

Many studies mentioned green infrastructures such as green wall and roof to be an effective strategy to reduce heat gain in buildings. Findings show that they are beneficial and environmentally responsive than sustainable facades. Additionally, they contribute to cleaner air by filtering pollutants, increases aesthetic value, reduces energy usage, and enhancing indoor air quality. In tropical climates, green wall and roof can reduce 10.5% of total energy consumption and 13% of district cooling demand of buildings, while improving air quality and energy efficiency [15]. A study conducted by Dede *et al.,* [16] used a physical model building to study the thermal insulation characteristics of green wall systems and the results shows in lower indoor temperatures with the green wall systems than the building with bare wall, highlighting the importance green wall systems for enhancing thermal insulation properties in buildings.

Window gardens as suggested in a study conducted by Ren and Tang, [17] in Xiamen, China, are proved to improve the indoor thermal environment attributed to shading, transpiration, and soil evaporation from vegetations of the window garden. Another study conducted by Ismail *et al.,* [18] suggested the usage of potted plants as a simple and sustainable strategy to improve the indoor temperature of buildings, mitigate global warming, and reduce the energy consumption in buildings.

A study conducted by Ran and Tang, [19] examined the cooling effect of combining green roof, external wall insulation, and night ventilation has shown that the green roof alone mainly absorbs heat from the indoor air. Another study also mentioned green roof can significantly reduce surface temperature and maintain 0.57 to 0.63 times lower than a traditional roof, preventing overheating during peak daytimes, conducted by Bevilacqua *et al.,* [20].

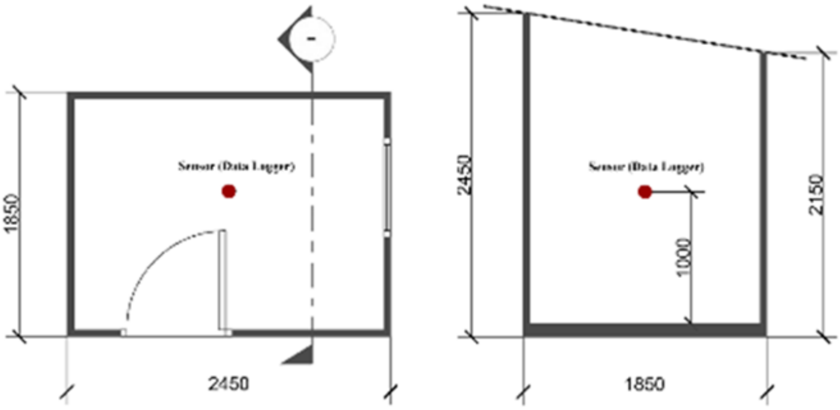
Several studies regarding green wall and roof strategies can be referenced for similarities in Brunei context. The architectural design elements can be referred to the neighbouring countries due to similar climate, but the fact that it is not directly referencing Brunei may raise confusion among the consumers and practitioners. Due to this, a study is needed to clearly outline the strategic implementation of bioclimatic practice using green wall and roof that is suitable for Brunei Darussalam. The research aligns with theoretical frameworks in building physics and sustainability. Moreover, the findings have the potential to influence the local building policies and economic practices, promoting broader adoption of green infrastructures for climate mitigation and energy efficiency. Finally, the research aims to quantify and confirm the effectiveness of green wall and roof systems in reducing the indoor temperatures with buildings in Brunei emphasizing their contribution to sustainable environment within the local context.

2. Methodology

2.1 Experimental Method

The comparative method of evaluating the effectiveness of green wall and roof in enhancing the indoor thermal environment by analysing two enclosures under the same settings, one with and one without green retrofit, is scientifically rigorous and practically relevant. This approach allows for a controlled experiment, isolating the impact of the green wall and roof.

The experimental building is a self-made enclosure that simulates the shape and size of a storeroom in a building. The enclosure was built using timber frames for support with cement boards as the wall panelling without insulation layer, and a zinc roofing for shading and rain shelter. The area of the enclosure is about $4.5m^2$ while the total volume is about $11m^3$. To ensure the experiments are running smoothly, another enclosure with the same dimensions and properties was built. This setup allows data comparisons between both enclosures without worrying too much about the external conditions in the experimental setup such as rainy weather. Enclosure A served as a control (no retrofit) while enclosure B was retrofitted with the selected green infrastructures, and both are naturally ventilated. Both enclosures were monitored simultaneously for a period of two weeks per green infrastructure. Additionally, no proper insulation nor waterproofing was installed on the wall and roof for both enclosures. This is to evaluate whether normal plants alone are able to affect the indoor temperature of the enclosures. The data were collected by data loggers as sensors assigned to each enclosure, as shown in Figure 1. All the experimental data were recorded at 1-hour intervals for 2 weeks period. Same group of plants are used for both green wall and roof throughout the experiment process. No additional plants or reduction of plants was made during the shift of experiment from green wall to green roof. This is to keep the consistency of the number and characteristics of the plants used in the whole experiment.



(a) Plan view (b) Section view

Fig. 1. Position of the data loggers in both enclosures

In the green wall experiment, the plants were arranged only on the surface of enclosure B that were mostly exposed to the sun throughout the day as shown in Figure 2. The plants are installed on the walls through the means of metal grating and metal hooks attached to each individual plants for ease of installation and relocation. This experiment design is inspired from similar studies on thermal insulation characteristics of green wall systems and cooling effect of window gardens by Dede *et al.* [16]. In the green roof experiment, all the plants from the green wall setup are relocated to the roof to act as the green roof design for this experiment as seen in Figure 3. This design of green roof using potted plants was inspired from the study using potted plants as a strategy to reduce indoor temperature in Malaysian climate [18].

2.2 Simulation Method

This section focuses on the identifying patterns, trends, or any cyclical behaviour in the temperature data over the course of the day via the DesignBuilder application. Modifications were made with the material settings to closely match with the experimental enclosure in terms of the type and layers. Anomalies or outliers that could be of interest will be identified through a time series analysis.

Fig. 2. Plants arrangement on the retrofitted enclosure for green wall setup

Fig. 3. Plants arrangement for the green roof setup

3. Results
3.1 Green Wall and Roof Experiment Results

Based on the data provided from the green wall experiment comparing two enclosures, one retrofitted with a green wall and one without, as shown in Figure 4, several conclusions can be drawn regarding the impact of the green wall on indoor temperature and overall indoor environment.

The enclosure with the green wall consistently had lower maximum indoor air temperatures than the enclosure without the green wall. During the hottest observed day (15th November at 2pm), Enclosure A had a peak indoor air temperature of 38.3°C, while Enclosure B had a much lower peak temperature of 34.8°C, showing 9.1% reduction. The 3.5°C gap indicates that the green wall helped cool down the indoor space, possibly reducing heat accumulation.

Although the maximum temperatures varied, both enclosures displayed similar trends in minimum indoor air temperatures during the experiment. Both enclosures had very similar low minimum temperatures, with Enclosure A recording 23.5°C and Enclosure B recording 23.6°C in the morning. This implies that although the green wall may have impacted maximum temperatures, it had minimal to zero influence on minimum temperatures. Throughout the experiment, Enclosure B consistently had lower average maximum indoor air temperatures than Enclosure A. Enclosure A averaged 36.3°C, while Enclosure B averaged 33.5°C, showing that the green wall helped decrease indoor temperatures, especially from 12pm to 3pm.

Based on the data provided from the experiment comparing two enclosures, one with a green roof and one without, as shown in Figure 5, several conclusions can be drawn regarding the impact of the green roof on indoor temperature and overall indoor environment.

Similar to the green wall experiment, the enclosure with the green roof (Enclosure B) consistently showed lower maximum indoor air temperatures than the enclosure without the green roof

(Enclosure A). During the warmest recorded time (3pm on 30th November), Enclosure A had an indoor air temperature peak of 39°C, whereas Enclosure B had a much lower peak temperature of 33.6°C, showing a 13% reduction. The 5.4°C variation shows that the green roof greatly cooled the indoor space, lowering heat accumulation.

As with the green wall experiment, both enclosures showed similar patterns for minimum indoor air temperatures throughout the experiment period. The lowest minimum temperatures recorded were very close for both enclosures, with Enclosure A reaching 23.5°C and Enclosure B reaching 23.4°C in the morning. This suggests that while the green roof influenced maximum temperatures, it had minimal effect on minimum temperatures.

The findings indicate that the enclosure retrofitted with green wall and roof experienced a significantly lower indoor temperature compared to the enclosure without. The maximum indoor temperature of the enclosure retrofitted with green wall and roof is also significantly lower compared to the enclosure without by 3.5°C and 5.4°C respectively. This result also aligns with similar studies in tropical regions, such as those conducted in Malaysia [18]. The high humidity and frequent rainfall in Brunei may have enhanced the cooling effect through increased evapotranspiration, suggesting a strong synergy between green infrastructure and local climate conditions.

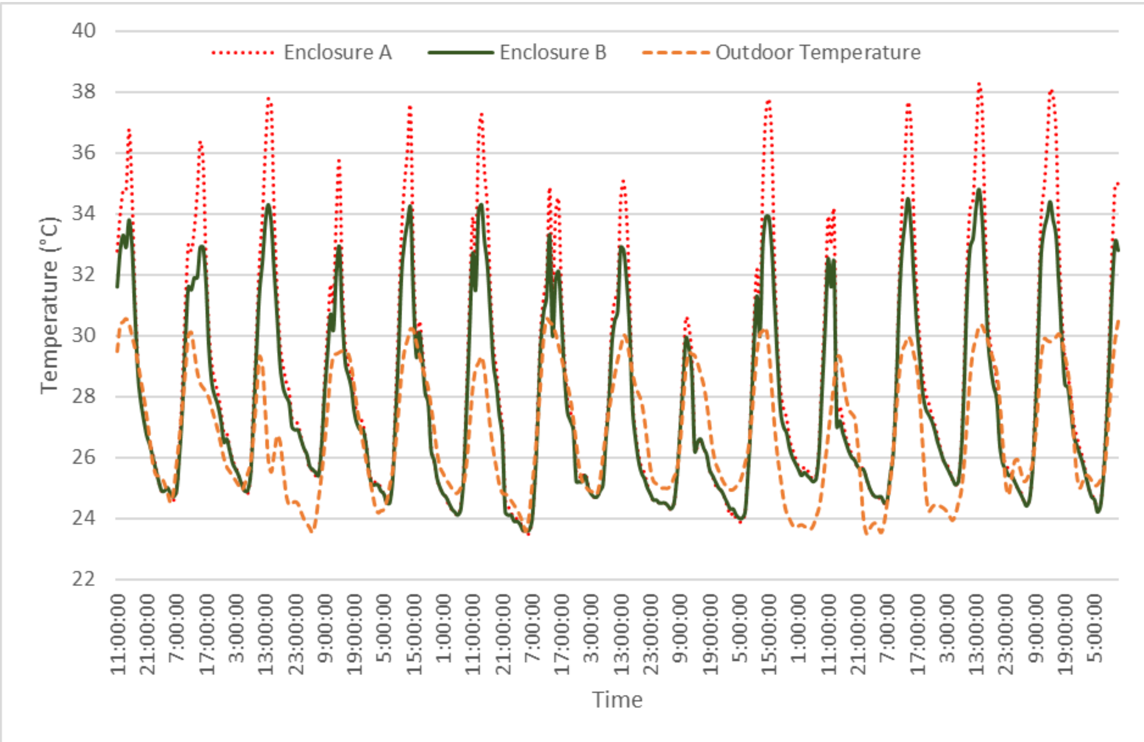


Fig. 4. Indoor temperature comparison for green wall experiment

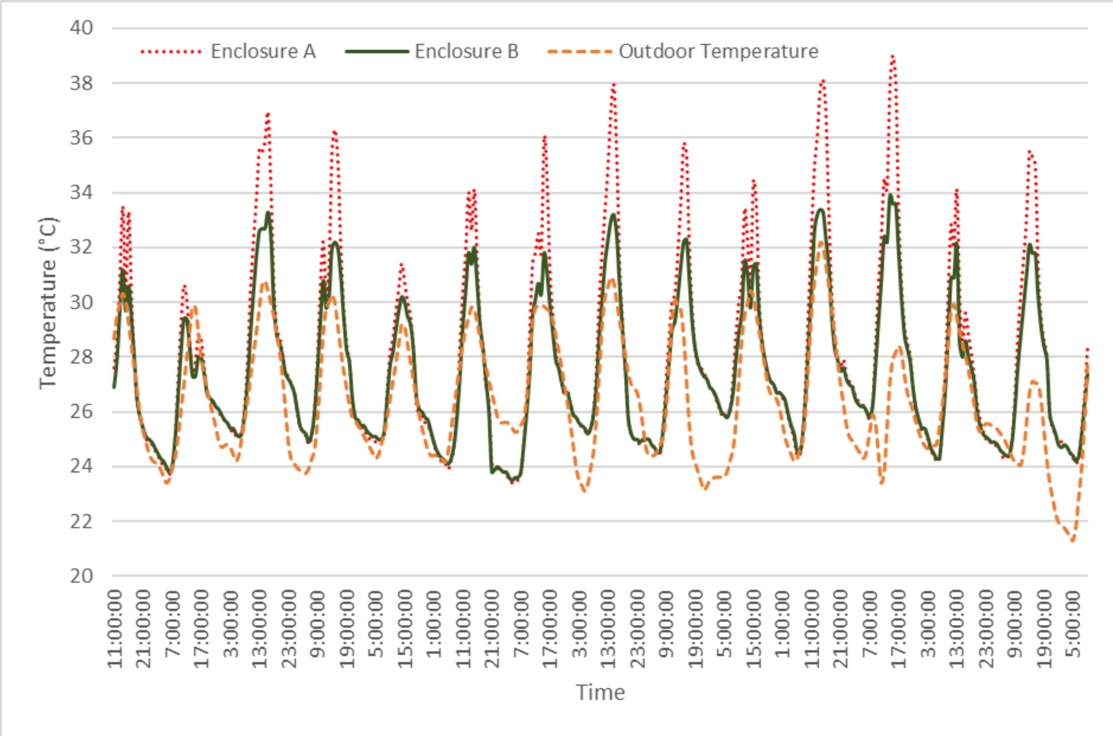


Fig. 5. Indoor temperature comparisons for the green roof experiment

3.2 Simulation Results

The graph in Figure 6 shows that the rolling averages smooth out the fluctuations and provide a clearer view of the overall trend throughout the day. Both measured and simulated temperatures show general increase during midday and a decrease towards the evening. Additionally, there appears to be a cyclical pattern with temperatures peaking around midday, which is typical for diurnal temperature variation. There are no significant anomalies or outliers in the rolling average, which suggests that the simulation does follow general trend of the measured data, although with consistently lower values.

Figure 7 shows similar rolling average lines illustrate the general trend throughout the day. The smoothed lines from the rolling averages do not show significant anomalies or unexpected deviations, suggesting that the simulation generally tracks the actual temperature variations but tends to be slightly lower or occasionally higher than the measured temperature values.

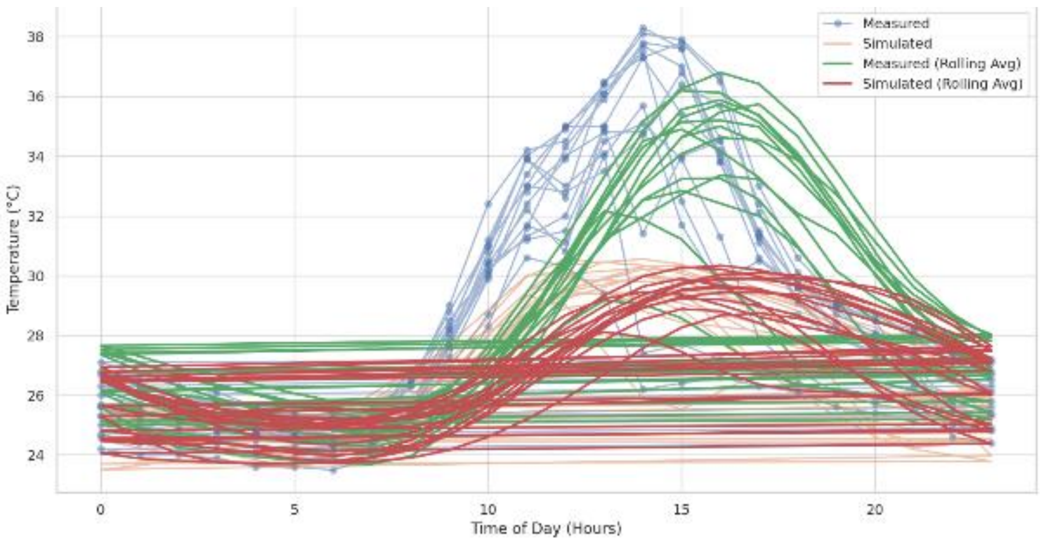


Fig. 6. Time series analysis for green wall simulation

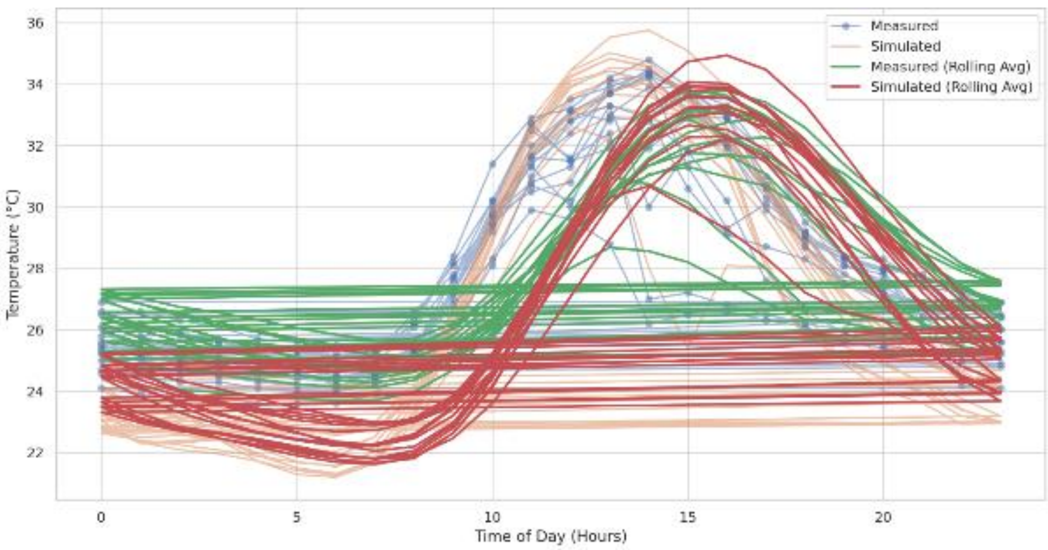


Fig. 7. Time series analysis for green roof simulation

Both simulations exhibit typical temperature behaviours expected in a daily cycle, with midday peaks and cooling periods towards the evening. The simulations, while generally capturing the shape of the daily temperature curve, show a consistent offset in the green wall experiment and less consistent behaviour in the green roof experiment, where it sometimes overestimates temperatures. These insights may be useful for refining simulation models to better match the measured data, especially how they react to peak temperatures and varying environmental conditions.

3.3 Implication of Findings

The observed decrease in maximum indoor temperature indicates that green infrastructure can effectively mitigate the heat gain within buildings, leading to a more stable and cooler indoor climate. This enhancement in thermal comfort can reduce the reliance on mechanical cooling systems, thereby creating more pleasant and habitable living and working spaces. By lowering indoor temperatures, green walls and roofs can help alleviate the discomfort associated with heat stress, which is particularly important for vulnerable populations such as the elderly and young children. Moreover, the psychological benefits of living and working in cooler, more natural environments should not be overlooked. Green walls and roofs do not only provide thermal comfort but also enhance aesthetic appeal and potentially improve the mental wellbeing through increased exposure to greenery. This dual benefit underscores the value of incorporating green infrastructure into building design, especially in the hot humid regions like Brunei.

The observed results also imply that buildings with green infrastructure can maintain comfortable indoor conditions with less energy-intensive cooling. This decrease in energy consumption can lead to a reduction in peak energy loads, alleviating pressure on the power grid and enhancing overall energy security. Furthermore, energy efficiency improvements contribute to the reduction of greenhouse gas emissions, aligning with global efforts to combat climate change. the initial investment in green walls and roofs can be offset by long term savings in energy costs. Building owners and developers may find that the payback period for these retrofits is relatively short, especially in climates where cooling costs constitute a significant portion of total energy expenditure. Additionally, the potential for government incentives or subsidies for energy-efficient building practices can further enhance the financial viability of green infrastructure projects.

The significant reduction in indoor air temperature observed in the enclosure retrofitted with green walls or roofs has substantial implications for health and wellbeing, particularly in Brunei Darussalam. In Brunei's tropical climate, where high temperatures and humidity are prevalent throughout the year, residents are at risk of heat-related illnesses such as heat exhaustion and heat stroke. By effectively lowering indoor temperatures, green walls and roofs can mitigate these health risks, contributing to safer living and working conditions. This is especially important for vulnerable populations, including the elderly, young children, and individuals with preexisting health conditions, who are more susceptible to the adverse effects of heat.

4. Conclusions

Integrating green wall and roof with building structures in Brunei can significantly enhance thermal comfort and promote climate-responsive design. These are shown to be achievable through several methods according to the literature reviews and experiments. The implementation of green roofs and green walls provides insulation, reduces heat absorption, and improves thermal comfort. The plants acted as solar shading to block direct sunlight to walls, windows, and roof. These green infrastructures also collect rainwater where it is used for cooling, further regulating the indoor temperature. Mostly, the plants used in the experiment required less maintenance. Surrounding trees and plants also provide shading and reduces heat island effect while improving overall thermal comfort. By the integration of green infrastructure, buildings in Brunei can create climate-responsive buildings that prioritize occupant well-being, reduce energy consumption, and contribute to a sustainable urban environment.

From the data collected from experiments and simulations shows reduction of heat gains during peak daytime which proves improvement in thermal comfort in the context of Brunei's weather and climate. In addition, the green wall and roof in the experiments are not properly built and installed with missing components from a proper green wall and roof, but still able to perform and lower the indoor temperature significantly. Moreover, green roof system showed data to be more effective than green wall to reduce the indoor air temperature during peak daytime.

The experiment would be more accurate through the use of proper materials realistic to a real building. Even better, studying with real buildings will reach a more rational contextual data in Brunei. Additionally, the current experiment utilized a makeshift design of a green wall and roof system, so incorporating a proper and accurate green wall and roof system would show a more realistic data than the current experiment. Another improvement would be extending the experiment periods up to a yearlong per experiment to show variations in weather conditions in Brunei, benefitting the accuracy and consistency of the temperature data to be gathered.

By demonstrating the effectiveness of green wall and roof in Brunei, this study provides a case study that can inform policies and practices in other tropical countries facing similar climatic challenges. These findings underscore the importance of integrating sustainable building practices into urban and rural planning to address climate change and promote environmental resilience.

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