Future Cities and Environment

# Enhancing Urban Sustainability through Green Roofs: A Thermal Performance Evaluation in Dubai

TECHNICAL ARTICLE

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## ABSTRACT

The Dubai Municipality has launched the 'Green Roofs Awareness Initiative' to achieve a green area per capita of 23.4 m$^2$ in the city. Given the numerous symptoms caused by the unprecedented urban expansion, green roofs and facades can provide various benefits to the city. This study intends to develop an evaluation method for the performance of green roofs (artificial ground reforestation) by quantifying the thermal environment functionality of a low-maintenance lightweight green roof. As a methodology, this study analyzed the change in the thermal environment of the surface, including sensible heat and latent heat, using four types of plants, namely Polytrichum Commune (PC), Thuidium Kanedae (TK), Anomobryum Filiforme (AF), and Kentucky Bluegrass (KB). The results showed that PC reduced the ground surface temperature by 2.58°C to 3.81°C while planting PC increased relative humidity (RH) from 48.0% to 93.3%. KB had the highest effect on humidity control, resulting in a 49.31% increase in RH. Regarding the temperature change by ground surface type, the surface temperature was 0.4 ~ 0.9°C lower for PC, AF, and TK at 18 ~ 24°C, while KB showed a 0.5 ± 0.2°C lower than the set temperature. KB did not show any significant change in temperature up to 24°C, but as the set temperature increased from 30 to 36°C, the surface temperature decreased remarkably. This research provides primary data that will serve to raise awareness, reduce installation costs, and systemize government support for green roofs in Dubai.

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## 1. INTRODUCTION

With the growing importance of eco-friendliness and energy issues, biotope creation and green building are gaining attention as sustainable city development and building technologies (Bibri, 2018; Zheng et al., 2019; Tang et al., 2015). Sustainable design based on the initial investment of the building was often avoided as an extra cost under the existing economic principles (Kim and Chung, 2019; Mushtaha et al., 2022). However, it is known that ecological building, which offers energy-saving and environmental preservation benefits during its lifetime, has more than expected outcomes, even if the cost of improving occupants' productivity is not included (Fregonara et al., 2017; Bragança et al., 2010). Artificial ground, in particular, occupies most of the external space and is an effective solution to the urban ecological problem as it provides a pleasant space for city residents through green plants (Liu et al., 2019). Artificial ground reforestation reduces temperature through transpiration and solar radiation mitigates ground and air temperature changes, and regulates the urban microclimate (Santamouris et al., 2018; Li et al., 2016).

In 2009, the Dubai Municipality launched the 'Green Roofs Awareness Initiative' to provide a manual on green roofs that recycle water from air-conditioners to irrigate plants on rooftops and facades of buildings (Construction Week, 2009). The initiative aims to achieve a green area per capita of 23.4 m$^2$ in Dubai (Khaleej Times, 2015). Green roofs are an emerging technology in Dubai that can provide various benefits to the city, which is suffering from numerous symptoms due to unprecedented urban expansion, including environmental protection (Abu-Hijleh and Jaheen, 2019; EcoMENA, 2018). To make this vision clear, Dubai has showcased several landmark projects, such as the Dubai Opera House Garden Green Roof and Living Green Wall in Dubai Wharf, featuring various climate-adapted shrubs such as Zoysia grass, Ruellia, Adenium, Agave, and Bougainvillea grown in a mixture of sweet soil and mineral wool growing media (Greenroofs, 2021) (Figure 1).

Recently, there has been an increased demand for low-maintenance and lightweight greening technology among the various types of green rooftops to minimize post-construction management costs and control urban microclimate (Mushtaha et al., 2016). Although considerable progress has been made in the development of soil, construction methods, and module systems, there is still a need to improve the selection of plants suitable for low-maintenance and lightweight greening in this region (Zhou et al., 2019; Taleb, 2016). Furthermore, as interest in wall greening as a vertical greening system is growing, there is active research on the systemic integration of plants, planting base layers, and irrigation facilities (Shushunova et al., 2020).

According to Zaid et al., there are several guidelines for green roof maintenance including the US Environmental Protection Agency (EPA) Design Guidelines and Maintenance Manual for Green Roofs, which is the most comprehensive, focusing on various maintenance elements except for monitoring performance (Zaid et al., 2022). According to Juricic et al., a green roof maintenance plan should include visual checks of the waterproofing layer, thermal insulation layer, heat fluxes, temperature values, load-bearing structure, and other maintenance elements (Juricic et al., 2021). Further, visual inspections include checking vegetation health and state of cleanliness, pest control, removal of infested or dried vegetation, debris collection, fertilization, pruning, reaping, seeding or replanting, scheduling actions after floods or storms, and watering (Juricic et al., 2021). Watering helps to induce the cooling and humidifying effect of green roofs, regardless of vegetation species (Zhang et al., 2020). Maintenance costs for intensive green roofs are generally higher than for extensive green roofs and conventional flat roofs (Zaid et al., 2022; Juricic et al., 2021).

Liu et al., took leaf surface temperatures using infrared thermal imagers and image planar analysis

**Figure 1** Dubai Opera House Garden Green Roof.

(Liu et al., 2012) (Figure 2). They found that plant temperature is affected by factors such as rate coverage, penetration rate, reflection rate, absorption rate, and evaporation rate. A later thermographic study also found a significantly lower surface temperature between a green roof and a conventional roof (Baryła et al., 2019). These studies consistently showed that green roofs have a significant impact in lowering roof surface temperature, thus reducing the urban heat island (UHI) effect, which is highly favorable for hot and arid Dubai.

Besides thermographic studies, the recently developed moss reforestation method, as an all-over reforestation method, is effective in controlling urban microclimates due to its high moisture content and high initial rainwater storage capacity compared to its weight (Radić et al., 2019). Extending this concept to green roofs in the hot and arid climate could be beneficial for Dubai. Therefore, this study aims to develop an evaluation method for the performance of green roofs (artificial ground reforestation) by quantifying the thermal environment functionality of a low-management lightweight green roof.

## 2. MATERIALS AND METHODS

### 2.1. EVAPOTRANSPIRATION OF PLANTS

Green roofs significantly reduce roof surface temperatures while also decreasing heat flux in buildings. Additionally, the plants on the green roof help increase its albedo, which cools the surrounding air by reflecting much of the sun's radiation (Coutts et al., 2013). Evapotranspiration of plants contributes to this benefit by making the surrounding air more humid, especially in hot and arid climates.

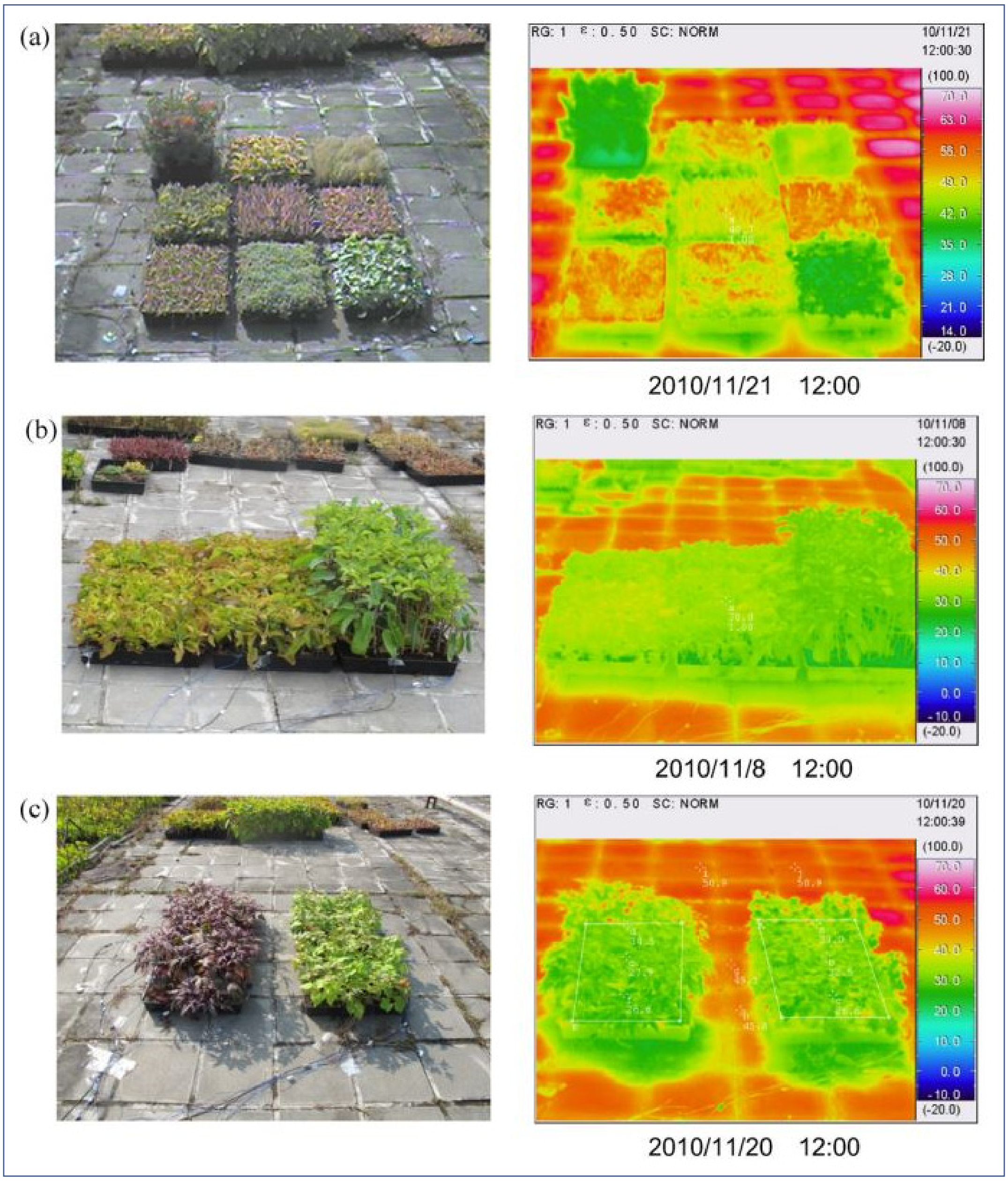


**Figure 2** Thermal effect analysis of various plants using thermography by Liu et al., 2019.

Evaporation is the process by which liquid water changes into gaseous water (Zhao et al., 2020). Transpiration refers to the process of evaporation from the plant's surface, primarily through the stomata of the leaves (Ouldboukhitine et al., 2014). The combination of evaporation and transpiration is called evapotranspiration (Kool et al., 2014). The study of evapotranspiration is crucial from the point of view of the energy cycle on Earth or hydrology, for the following reasons. First, efficient management and use of water can be achieved. Second, it helps in understanding the energy cycle. Third, evapotranspiration returns the net radiant energy to the atmosphere in the form of latent heat, which serves to transport the energy to distant regions (Figure 3). Fourth, it can influence the exchange of trace gases such as Methane ($CH_4$) and Carbon Dioxide ($CO_2$) between the surface and the atmosphere, helping in understanding their cycle (Yin et al., 2016; Dabous et al., 2022; Valipour, 2015).

Evapotranspiration plays a crucial role in the carbon balance of ecosystems concerning soil moisture status (Eiz et al., 2021). Therefore, it is necessary to understand evapotranspiration since it has a multifaceted effect (Lian et al, 2021). Evapotranspiration from plant communities is currently being studied extensively, but many issues still exist (Sawada et al., 2018).

Evapotranspiration from plant communities is influenced by solar radiation, atmospheric humidity, temperature and turbulence, stomata conditions, plant community structure, and soil and plant moisture conditions (Devitt et al., 2011). There are several methods for predicting and diagnosing evapotranspiration, but among them, the simplest and most widely used is the Penman-Monteith complex equation (Tabari and Talaee, 2011). Initially used to represent evapotranspiration for a single leaf, this equation is now used in many variations to explain the interaction between global crops and the atmosphere (Djaman et al., 2019).

Penmann viewed the evaporation process from two perspectives: an aerodynamic perspective, which involves a turbulent transport process by eddy diffusion, and an energy balance related to the distribution of radiant energy (Lang et al., 2017; Celestin et al., 2020). Monteith combined the energy balance, aerodynamic parameters, and surface temperature to create a more generally helpful equation (Valiantzas, 2013). He derived the equation found by Penman using the thermodynamic wet-bulb temperature and the Clausius-Clapeyron (CC) equation. Going one step further, he introduced the concept of surface resistance to water vapour flux based on Ohm's law of electromagnetics when water vapour is not saturated. He expressed it as Equation (1) below.

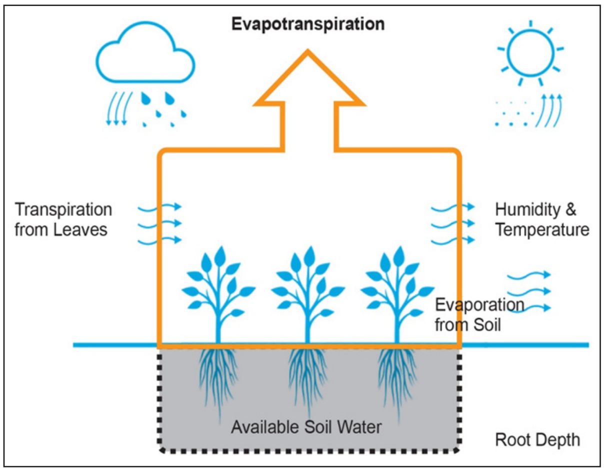


**Figure 3** Evapotranspiration Model of Plants.

$$\lambda E = \frac{\Delta A + \rho c_p [e_w \{T(z)\} - e(z)] r_{ah}}{\Delta + \gamma (r_{av} + r_{st}) / r_{ah}} \tag{1}$$

The Penman-Monteith equation includes several components, the first of which is the stomatal resistance. Rah and Rav represent the aerodynamic resistance to heat and water vapour between the plant and height, respectively. ρ is the air pressure, r is the dry-humidity constant, e is the water vapour pressure, ew is the saturated water vapour pressure, and Δ is the temperature change. The difference in saturated water vapour pressure, cp, represents the specific heat of static pressure, and A is the available energy (Dubovský et al., 2021; Schymanski and Or, 2017; Celestin et al., 2020).

## 2.2. ENVIRONMENTAL CHARACTERISTICS OF GRASS AND MOSS

Grass is widely recognized for its ability to regenerate lands with poor water-holding capacity and contribute to city beautification by cooling warm weather and stabilizing the soil (Mganga et al., 2021). Among grasses, Kentucky Bluegrass (Poa pratensis L.) is particularly popular for city landscaping due to its drought-tolerant characteristics even with reduced growth due to water scarcity (Cui et al., 2021).

Bryophytes are non-vascular land plants comprising three groups: mosses, liverworts, and hornworts (Asakawa et al., 2013). Moss primarily inhabits wet areas but can also grow on rocks and concrete buildings under suitable conditions (Chairunnisa and Susanto, 2018). In Dubai, moss is commonly found in shady and wet areas, and it can even grow on steep slopes where trees and shrubs inhabit, helping to prevent soil erosion during winter rainfall (Taleb, 2014; Ah-Peng et al., 2017).

The growth form of bryophytes is classified based on the growth form of each individual and the population (Schmalholz and Granath, 2014). The growth pattern of each individual can be divided into orthotropic and plagiotropic, with orthotropic shoots growing perpendicular to the medium to which the stems are attached and plagiotropic shoots growing horizontally in the medium (Myszczyński et al., 2019; Mushtaha et al., 2012; Chmara et al., 2015).

Compared to higher plants, moss absorbs moisture in a relatively diverse way (Anderson et al., 2010). Even in a dehydrated state, it can survive without dying and rapidly photosynthesizes and grows when water is supplied (Turetsky et al., 2012). While some mosses absorb water through rhizomes, most absorb water through their entire plant surface (Song et al., 2016). The amount of water that bryophytes can absorb varies greatly depending on the type, but it is generally known that they can absorb 50 – 2,000% of their dry weight in water (Salameh et al., 2023). Moss dried by sunlight on a clear day has a moisture level of about 5% and can survive in a dry state at temperatures as low as –196°C and as high as 100°C for a certain period (Staunch et al., 2012; Rousk et al., 2014). Due to their high cation substitution capacity, mosses can even absorb low concentrations of nutrients (Cruz de Carvalho et al., 2012).

## 2.3. METHODS AND PROCEDURES OF RESEARCH

In this study, the thermal environment's surface temperature change was analyzed using four plants to evaluate the thermal environment of ground cover (Greenview, 2023; Lai et al., 2019). The study procedure involved three steps. First, measure the difference in the surface temperature of each type according to the temperature change. Second, measure the difference in temperature distribution for each space height due to the ground cover. Third, analyse the temperature change characteristics of the space, such as sensible heat and latent heat, based on the results obtained.

The ground cover used in the experiment included the Kentucky Bluegrass (KB) grass and three types of mosses, namely Polystichum commune (PC), Thuidium kanedae (TK), and anomobryum filiforme (AF) (Table 1). These four types are the most popular grass and mosses in Dubai (Insideout, 2019; Gardenista, 2013).

To investigate the changes in temperature and humidity of indoor spaces by plants, the changes in temperature and humidity of the indoor space according to temperature conditions were measured in a closed glass chamber of dimensions 2 × 1.3 × 1.8 m and a total volume of 4.68 $m^3$ (Gardenista, 2013) (Figure 4). This chamber was constructed indoors and fitted with LED artificial lights, and the chosen plants were sequentially changed during the experiment.

Using a thermo-hygrometer (PCE-VDL 16I, UK), the temperature was measured at four different heights from

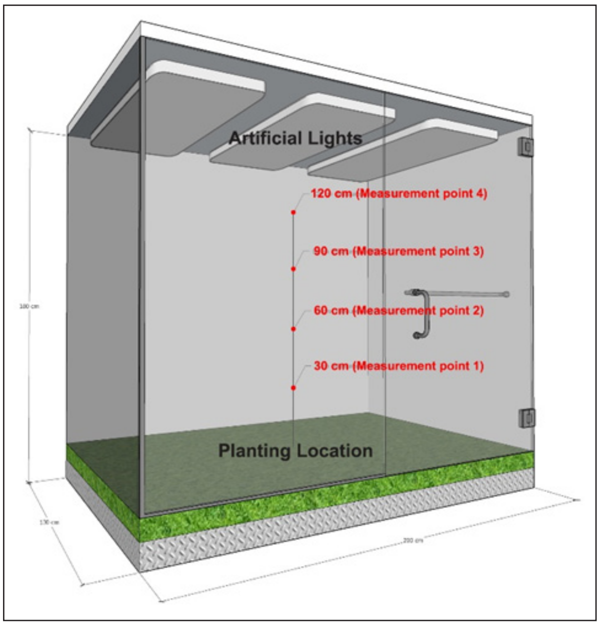


**Figure 4** Glass Chamber Model.

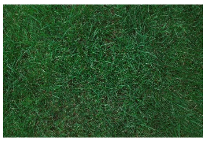
| MOSSES | ENVIRONMENTAL CHARACTERISTICS | IMAGES |
|---|---|---|
| Kentucky Bluegrass (KB) | – Self-spreading and able to recover from damage<br>– Grows best in full sun.<br>– It has shallow roots, thus drought-tolerant (Staunch et al., 2012). |  |
| Polytrichum Commune (PC) | – Also known as common hair cap, great golden maidenhair, great goldilocks, common hair cap moss, or common hair moss<br>– Few bushes<br>– Cultivate in well-drained, sunny clay soil |  |
| Thuidium Kaneda (TK) | – Grows in groups like a carpet on rocks |  |
| Anomobryum Filiforme (AF) | – Grows in a grassy form on the sunny side of the ground or on the bedrock, it<br>– The scaly leaves are epiphytic<br>– Growing in layers regardless of dryness and humidity |  |

**Table 1** Environmental characteristics of grass and mosses.

the surface, i.e., 30 cm, 60 cm, 90 cm, and 120 cm (Ghosh et al., 2018; Li et al., 2010). Measurements were made at intervals of 5 minutes. The glass chamber was fitted with a ventilation system that supplies fresh air to maintain the specified temperature and humidity and allows the plants to breathe and perform photosynthesis (Tabares-Velasco and Srebric, 2012). The required air volume was 800 $m^3$/h, and the maximum number of ventilations in the room was set at 2 times/h (Ramasubramanian et al., 2019).

During the measurement period of this study from December 2020 to February 2021, the relative humidity remained relatively constant between 40% to 60%, while the temperature varied. The surface temperature of moss was measured for each set temperature from 18°C to 36°C to determine the gradient of change for each type of moss according to the change in the set temperature (Torpy et al., 2014). The temperature was lowered by two degrees every two hours to calculate the gradient for each temperature range for each plant. The difference in temperature change for each plant was measured to determine the effect of the presence or absence of plants. The indoor environment measurement was repeated five times for each plant (Tabares-Velasco and Srebric, 2012).

To perform statistical analysis of the experimental results, the significance of the difference between the mean values was determined using Duncan's multiple range test (DMRT 5%) (American Psychological Association, 2020) among ANOVA (analysis of variance) using the IBM SPSS Statistics 26 program (George and Mallery, 2019).

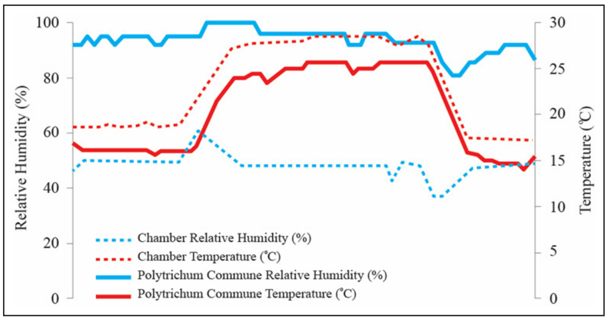


**Figure 5** Change in temperature and humidity according to temperature change of polytrichum commune.

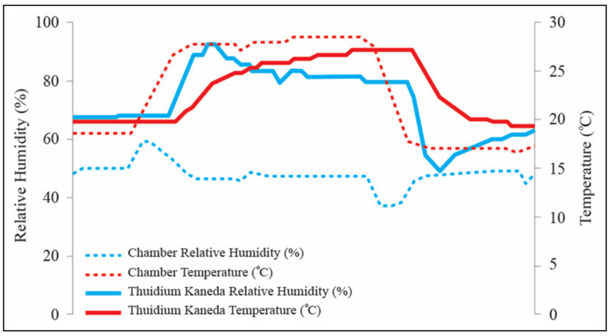


**Figure 6** Change in temperature and humidity according to temperature change of thuidium kaneda.

# 3. RESULTS

## 3.1. CHANGES IN TEMPERATURE & HUMIDITY DUE TO GROUND SURFACE

Plants release moisture through transpiration, which helps regulate the temperature and humidity of dry indoor air, creating a comfortable environment (Han et al., 2021; Wang et al., 2014; Kazemi et al., 2020). When plants are placed above an indoor space with a higher temperature, their physiological activity can reduce the temperature. Specifically, in high-temperature rooms, there is a tendency to lower the temperature and maintain a suitable thermal state within the comfortable indoor temperature range (Figures 5 to 8).

## 3.2. DIFFERENCE IN SURFACE TEMPERATURE BY GROUND SURFACE

The results of the measurements of the change in surface temperature for each set temperature of moss are as follows. At the set temperature of 18°C, the surface temperature of PC tended to decrease by about one degree or more, while there was almost no change according to the treatment of TK. At 24°C, there was no change in TK, but the surface temperature of AF and PC decreased by 0.5°C.

At 30°C, the surface temperature of TK decreased the least, and the surface temperature showed a tendency to fall in the order of AF < PC < KB. Finally, at a relatively high temperature of 36°C, the surface temperature of TK, AF, and PC decreased by about 0.3°C, while the surface temperature of KB decreased by about 0.5°C (Figure 9).

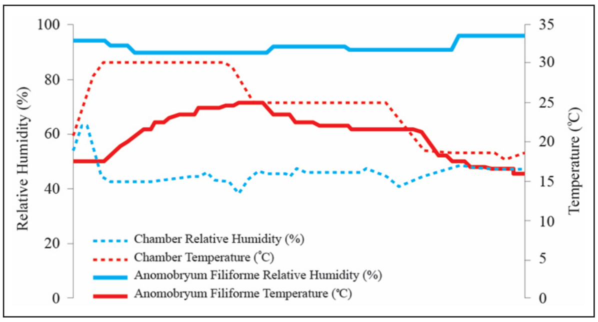


**Figure 7** Change in Temperature and humidity according to temperature change of anomobryum filiforme.

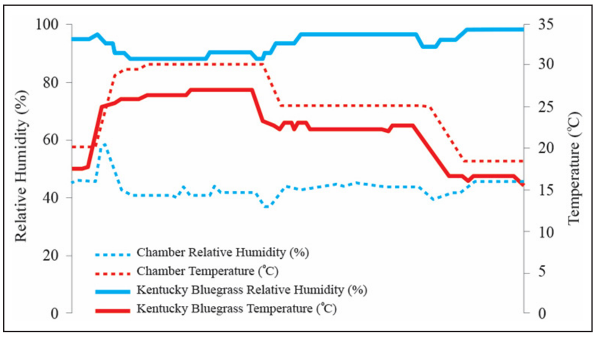


**Figure 8** Change in Temperature & Humidity according to Temperature Change of Kentucky Bluegrass.

### 3.3. CHANGES IN LATENT HEAT BY GROUND SURFACE

In this study, the latent heat for each type of moss was calculated since the increase in latent heat is related to the change in entropy. The results are presented in Figure 10, which shows the amount of change in absolute humidity when absolute humidity changes without temperature change.

Under 18°C, the latent heat in the absence of moss was 5.31 kcal/kg, which was the same as the place with moss. AF had a latent caloric value of 1.33 kcal/kg, TK had 1.99 kcal/kg, and PC had 3.32 kcal/kg. At 24°C, all of the latent caloric values of moss were high, with AF having a latent caloric value of 4.63 kcal/kg. The latent heat concentration of PC and KB was 3.96 kcal/kg, TK was 2.64 kcal/kg, and the latent heat in the absence of moss was 2.64 kcal/kg.

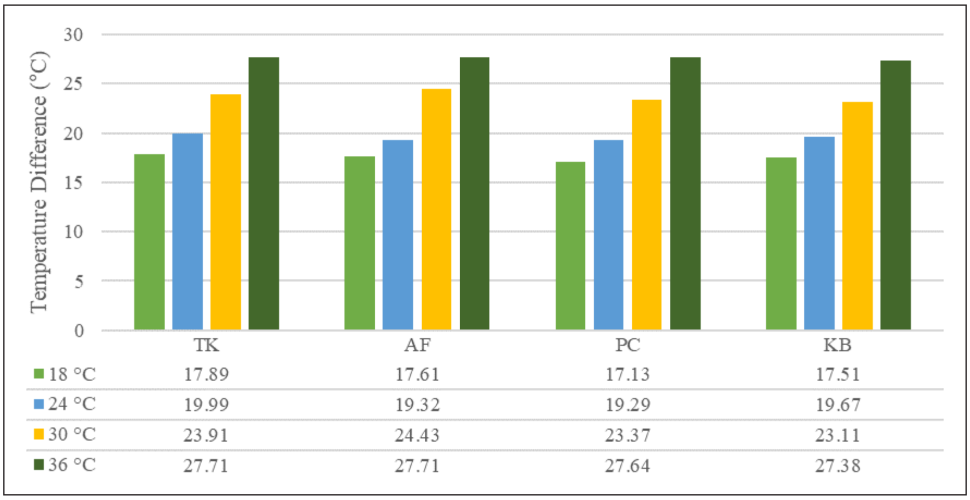
Under 30°C, PC was 5.26 kcal/kg, and KB was 4.60 kcal/kg, both higher than without plants. At a high temperature such as 36°C, the latent heat of 4.58 kcal/kg of AF was similar to the 3.93 kcal/kg of the state without moss, indicating a similar latent heat. It was found that TK had a very high latent calorific value of 9.16 kcal/kg.

In summary, the presence of plants tended to increase the latent heat when the temperature increased to 24°C but decreased it to 18°C, which is lower than the optimum temperature for growth. Among the experimental materials, PC and KB tended to improve their latent heat as the temperature increased continuously.

## 4. DISCUSSION

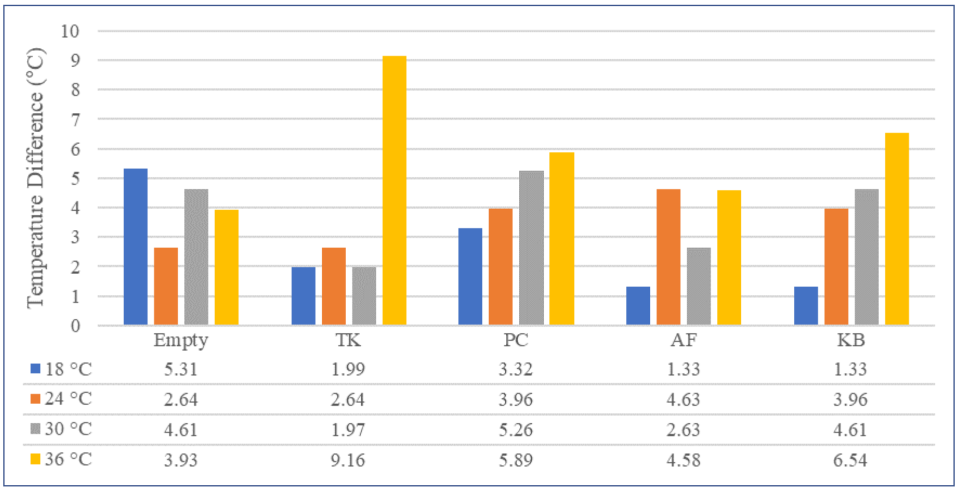
The key findings of this study are summarized as follows. Firstly, PC was found to reduce the space temperature by 2.58°C to 3.81°C between 18°C and 36°C. Secondly, the RH increased from 48.0% to 93.3% with the planting of PC. Thirdly, KB reduced the indoor temperature by 2.28 ± 3.90°C, with no difference in the reduction rate between high and low temperatures, and increased RH by 49.31%, showing the highest effect on humidity control.

Regarding the temperature change by ground surface type, at relatively low temperatures up to the set temperature of 18 ~ 24°C, the surface temperature was 0.4 ~ 0.9°C lower than the set temperature for PC and AF. TK showed similar results to the set temperature, and KB



| | TK | AF | PC | KB |
|---|---|---|---|---|
| 🟩 18 °C | 17.89 | 17.61 | 17.13 | 17.51 |
| 🟦 24 °C | 19.99 | 19.32 | 19.29 | 19.67 |
| 🟨 30 °C | 23.91 | 24.43 | 23.37 | 23.11 |
| 🟩 36 °C | 27.71 | 27.71 | 27.64 | 27.38 |

**Figure 9** The Difference in the Surface Temperature at 18–36.



| | Empty | TK | PC | AF | KB |
|---|---|---|---|---|---|
| 🟦 18 °C | 5.31 | 1.99 | 3.32 | 1.33 | 1.33 |
| 🟧 24 °C | 2.64 | 2.64 | 3.96 | 4.63 | 3.96 |
| ⬜ 30 °C | 4.61 | 1.97 | 5.26 | 2.63 | 4.61 |
| 🟨 36 °C | 3.93 | 9.16 | 5.89 | 4.58 | 6.54 |

**Figure 10** Increase in Latent Heat of Mosses and Grass at 18–36.

showed a 0.5 ± 0.2°C lower surface temperature than the set temperature.

Furthermore, TK showed less difference from the set temperature at relatively low temperatures than at high temperatures. On the other hand, in KB, there was no significant change in temperature up to 24°C, where the set temperature was relatively low. However, as the set temperature increased from 30°C to 36°C, the surface temperature decreased remarkably.

Based on the results, all tested plants showed a measurable thermal effect and could be used in green rooftop designs in Dubai. PC and KB were found to pull the chamber temperature down compared to TK and AF while maintaining high RH levels, thus potentially helping to alleviate the urban heat island effect in densely populated areas of Dubai. Nevertheless, both TK and AF mosses could still be used to promote urban biodiversity on green rooftops. Further studies are required to determine the thermal effects of various combinations of these plants.

## 5. CONCLUSIONS

In conclusion, this study investigated the thermal and humidity effects of different types of moss on indoor air quality, with a focus on their potential use in green rooftop designs in Dubai. The results demonstrated that all tested plants had a measurable thermal effect, with PC and KB showing the most promising results in terms of reducing space temperature and increasing RH levels. These findings suggest that implementing green roofs in Dubai could help alleviate the urban heat island effect and promote biodiversity, while also improving air quality and providing a sustainable solution for green construction.

However, despite the potential benefits of green roofs, the implementation of such initiatives in Dubai faces several barriers, including a lack of systematic governmental support, high installation costs, limited awareness, and insufficient data quantifying the benefits. To overcome these challenges, innovative research and design solutions are needed to promote the wider adoption of green roofs in Dubai and other densely populated urban areas. With further investigation, green roofs could become an essential element of sustainable and green construction in Dubai, contributing to the city's environmental goals and creating a more livable and enjoyable urban environment.

## DATA ACCESSIBILITY STATEMENT

New data were created or analyzed in this study. Data will be shared upon request and consideration of the authors.

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## COMPETING INTERESTS

The authors have no competing interests to declare.

## AUTHOR CONTRIBUTIONS

All authors contributed significantly to this study. C.J. and J.A. identified and secured the example buildings used in the study. The data acquisition system and sensors were designed and installed by C.J. and M.A.I. C.J. and A.C. were responsible for data collection. J.A. and M.A.I. performed data analysis. The manuscript was compiled by J.A. and C.J., and reviewed by M.A.I. and A.C. All authors have read and agreed to the published version of the manuscript.

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