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SIMULATION-BASED ANALYSIS OF THE EFFECT OF GREEN ROOFS ON THERMAL PERFORMANCE OF BUILDINGS IN A TROPICAL LANDSCAPE

Análise baseada em simulação do efeito dos telhados verdes no desempenho térmico de edifícios em uma paisagem tropical

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ABSTRACT

Apart from the ever- increasing population of most tropical urban cities, high ambient temperature, deteriorated comfort conditions, highly polluted environments are but a few of the problems these cities are confronted with. In the long run, increase energy demands both for production and the provision of comfortable spaces becomes necessary even though it's a very scarce resource. It is widely known that Urban heat island (UHI) can significantly affect building's thermal performance and as such, this study was conducted to find out how green roof which is a mitigating factor can reduce the thermal discomfort in indoor spaces. By means of dynamic simulation in EnergyPlus software, a numerical comparative analysis between eight scenarios was done in a tropical climate of Ghana, taking into account climatological, thermal, and hydrological variables. Two factors: Leaf Area Index (LAI) and Soil depth were the main determinants of the comparative analysis. From the results, 5 out of the 8 scenarios was seen to all have performed better leading to a 1.5°C temperature reduction. Out of the 5, LAI5/70-150mm and LAI2/500mm suggest that at every point, there could be a reduction in indoor temperature if either LAI is larger or substrate depth is deep. A larger LAI and a deeper depth could also produce a favorable result (LAI5/500mm) though after a certain threshold, their effect weakens. Based on the findings, it is highly recommended that green roofs become part of the solution towards the fight against indoor thermal discomfort and not mechanical ventilation which could have a dire consequence on an already scare resource which is energy.

Keywords: Urban Heat Island; Thermal comfort; Kumasi; Urbanization; Climate change.

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ANÁLISE BASEADA EM SIMULAÇÃO DO EFEITO DOS TELHADOS VERDES NO DESEMPENHO TÉRMICO DE EDIFÍCIOS EM UMA PAISAGEM TROPICAL

Simulation-based analysis of the effect of green roofs on thermal performance of buildings in a tropical landscape

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RESUMO

Além da população cada vez maior da maioria das cidades tropicais, a alta temperatura ambiente, as condições de conforto deterioradas e os ambientes altamente poluídos são apenas alguns dos problemas que essas cidades enfrentam. No longo prazo, aumentar as demandas de energia tanto para a produção quanto para o fornecimento de espaços confortáveis torna-se necessário, embora seja um recurso muito escasso. É amplamente conhecido que a ilha de calor urbana (UHI) pode afetar significativamente o desempenho térmico do edifício e, como tal, este estudo foi realizado para descobrir como o telhado verde, que é um fator atenuante, pode reduzir o desconforto térmico em espaços internos. Por meio de simulação dinâmica no software EnergyPlus, foi feita uma análise numérica comparativa entre oito cenários em um clima tropical de Gana, levando em consideração variáveis climatológicas, térmicas e hidrológicas. Dois fatores: Índice de área foliar (IAF) e profundidade do solo foram os principais determinantes da análise comparativa. A partir dos resultados, 5 dos 8 cenários foram vistos e todos tiveram um desempenho melhor, levando a uma redução de temperatura de 1,5 ° C. Dos 5, LAI5 / 70-150mm e LAI2 / 500mm sugerem que em todos os pontos, pode haver uma redução na temperatura interna se o LAI for maior ou a profundidade do substrato for profunda. Um LAI maior e uma profundidade mais profunda também podem produzir resultados favoráveis (LAI5 / 500mm), embora após um certo limiar seu efeito enfraqueça. Com base nas constatações, é altamente recomendável que os telhados verdes se tornem parte da solução para o combate ao desconforto térmico interno e não à ventilação mecânica, o que pode ter consequências terríveis em um recurso já assustador que é a energia.

Palavras-chave: Ilha de Calor Urbano; Conforto Térmico; Kumasi; Urbanização; Mudanças climáticas.

INTRODUCTION

The world today faces one of its worst challenges in the form of climate change. Mainly due to urbanization, most cities experience serious Urban Heat Island (UHI) effects which has been reported to be very devastating. For instance, Cui et al. (2017) illustrated a long-term study from 1961 to 2014 which indicated that the UHI effect is significant in Beijing. Its urban-rural temperature variance can reach as much as 8°C in the winter night which has been regarded as one of the major environmental problems confronting the city's residents. Globally, it’s been reported that average temperature values have risen by 1.5°C with this figure increasing by the years (BBC World news).

The issue of UHI effect has been reported to impair the urban environment and human health in a number of ways. According to Lulla et al. (2015) as cited in Zhang et al. (2019), the rise in temperature may increase the temperature of standing water and affect the diversity of life within. It may cause changes in patterns of wind and rain. Zhang et al. (2019) further report that the UHI effect is known to be associated with urban haze. Kjellstrom et al. (2016) concluded that the phenomenon can be expected to decrease worker productivity in the city by as much as 10% during the daytime.

Indeed several more studies have outlined the damning effects of this occurrence. Mortalities, especially for the elderly was reported by Rocklöv et al. (2014). Furthermore, raises in energy consumption resulting in deteriorated air quality and increased greenhouse gas emissions are also effects of UHI reported by Stafoggia et al. (2008) and Xu et al. (2018). Whiles outlining these effects, other studies have proposed methods for assuaging UHI. Chen and Wong (2006), Oliveira et al. (2011) and Chun and Guldmann (2018) all proposed the expansion of urban green spaces as one effective method. The use of green roofs to cool building surfaces has also been reported in a large numbers of studies (Bing, 2011, Sun et al., 2013; Zheng, 2014; Li et al., 2015; Karachaliou et al., 2016) as an equally method.

Gartland (2008) also distinguished between three major actions that can be implemented at the community level to mitigate UHI effect: cool roofing, cool paving, and cooling with trees and vegetation. Navigant Consulting (2009) listed four major mitigation technologies: cool roofs, cool pavements, green roofs and urban green areas, and vehicle paint. From the above discussion, though UHI poses a great treat to the environment, there are certain practices that can lessen it. The purpose of this paper is to find out how much indoor spaces can be thermally comfortable by using green roofs.

1 LITERATURE REVIEW

Literature for the study includes thermal comfort as well as related studies on green roofs as a mitigating factor for Urban Heat Island effect.

1.1 Thermal Comfort

Thermal comfort has been defined as the ‘condition of mind in which satisfaction is expressed with the environment’ (ASHRAE Handbook, 2008), whereas thermal sensation is the state of mind expressing the person's evaluation of its thermal environment (Zhang and Zhao, 2009). Pino et al. (2012) also defines thermal comfort as the physical and psychological wellness of an individual when temperature, humidity, and air movement conditions are favourable for the activity that must be developed. Both definitions gives an apt description of what one should look out for to be thermally comfortable.

Ali and Patnaik (2018) posits that humans are usually comfortable within a relatively small range of temperature and humidity conditions, roughly between 20–26.7°C and 20-80% relative humidity (RH), often referred to on psychrometric charts as the “comfort zone.” In a tropical country like Ghana, these values are rarely achieved making indoor spaces very uncomfortable. Lelieveld et al. (2016) investigated projected climate change and temperature extremes specifically in the Middle East and North Africa (MENA), concluding that while at present the warmest nights are on average below 30 °C, they will surpass 34 °C by the end of the century

(RCP8.5). Maximum temperature during the hottest days, 43°C at present, is expected to increase to nearly 46°C by the middle of the century, and to reach nearly 50 °C by the end of the century in the same scenario.

The average duration of warm spells is also expected to increase. Shilei et al. (2018) asserts that higher requirement of indoor thermal comfort always comes with our buildings consuming more energy. UHI poses a great danger to all humanity with its chain of reactions. But as has been observed by Saaroni et al. (2018), compounding the UHI effect is the ongoing increase in temperature due to regional and global climate change. An account by the Urban Climate Change Research Network reported on by Rosenzweig et al. (2015) shows that mean annual temperatures in 39 cities have increased at a rate of 0.12 to 0.45 °C per decade over the 1961 to 2010 time period, based on data from the NASA GISS GISTEMP. Moreover, projections from 35 global climate models for two representative concentration pathways (RCP4.5 and RCP8.5) show that mean annual temperatures in 100 cities are projected to increase from 0.7 to 1.5 °C by the 2020s, 1.3 to 3.0 °C by the 2050s, and 1.7 to 4.9 °C by the 2080s. Chen and Ng (2012) reports on the importance of outdoor thermal comfort for city development. The authors postulated that urban outdoors and daily activities contribute to urban liveability and vitality. Aljawabra and Nikolopoulou (2010) argued that solar radiation influences the number of visitors and activity in these spaces.

The study of Rose (2010) in Chennai, assessing the impact of urbanization of thermal comfort revealed significant decrease in the thermal comfort conditions due to urbanization and increasing discomfort in daytime temperatures over years. Da Silveira Hirashima et al. (2016) also surveyed the two squares located in the city of Belo Horizonte, Brazil to assess their thermal comfort using PET index over summer and winter seasons. The study suggested the incorporation of design strategies such as shading, exposure to the wind and providing increased environmental diversity to improve urban environments. Thermal comfort from the above discussion tends to be very expensive (use of air-conditioners) and therefore if design strategies could substitute, then it must be carefully looked into.

For instance, Green roofs have been known to reduced indoor temperature values by 3°C to 4°C when outdoor temperatures values were between 25°C and 30°C (Peck 1999). Again, an identified added advantage of a green roof as indicated by Dunnett and Kingsbury (2008) is for every decrease in internal building air temperature of 0.5°C, may reduce electricity use for air-conditioning up to 8%.

1.2 Related Studies on UHI and Green Roofs

Many studies have reported on the relationship between Urban Heat Island effect, green roofs and its consequence on thermal performance. For instance, Karachaliou et al. (2016) reported that the surface temperature of a green roof is 15°C lower than that of a conventional roof. In the study of Bing (2011), the author revealed that a green roof can reduce the urban surface temperature by 30–60 °C. When Sun et al. (2013) compared surface temperature reductions of green roofs in different regions; their results showed that hot and dry regions reported the maximum reduction. These results are so because of the characteristic nature of green roofs. The fact that these roofs are in sync with nature, it turns to perform better.

Previous studies have shown that green roofs reduce the thermal performance of buildings through evapotranspiration, photosynthesis, solar shading, and thermal insulation of substrates (Raji et al., 2015; Santamouris et al., 2007). Santamouris (2012) observed that green roofs cool down the temperature because of the direct coverage of plants and the opening of stomata that allows transpiration during daytime. The author further stated that the textures of leaf surface and albedo effect also take place. The vegetation stores the heat and cools down the air. The author in a research in the US indicated that vegetated rooftops decreased the peak temperature from 0.5 K to 3.5 K; along with dropping of temperature, the albedo increased from 0.05 up to 0.61 (Santamouris, 2012). To this end, Saadatian et al. (2013) in their study concluded that improvement in thermal performance is due to increment of shading, better insulation and high thermal mass of the roof system in totality.

Zhang et al. (2018) observed that in conventional roofs, incoming energy is mostly translated into sensible heat flux increasing the surface's surrounding air temperature. In a much-correlated study, Kolokotsa et al. (2012a, 2012b) completed a comparative analysis of cool roofs and green roofs in Crete, Rome and London with respect to a conventional roof. The study revealed higher mitigation potential of UHI for albedo higher than 0.6 for cool roofs and leaf area index higher than 1 for green roofs. Several field experiments around the world have also shown that daily maximum surface temperature of cool and green roofs can be 10–30°C lower than that of conventional roofs (Yang et al., 2015; Santamouris, 2013; Takebayashi and Moriyama, 2009).

The purpose of this study is to experimentally probe into the effects of green roofs in improving comfort conditions in Tropical Ghana. Lessons from the study could impact the understanding and application of design recommendations by built environment professionals, especially architects.

2 MATERIALS AND METHOD

The study employed the experimental strategy where version 5.0.2 Design Builder and Energy Plus version 5.8 were used. The site location parameters such as latitude and longitude, time zone, site elevation above sea level and the average monthly ground temperatures of Kumasi the Capital of Ashanti Region, were specified in the Input Data File. Due to the test cells contact with the ground, the ground temperature values were specified using the Design Builder program as the outside temperature values. The Latitude and Longitude for the test cell is 6.8^o and -1.33^o respectfully. The time zone is 0 hours and the elevation above sea level is 258m. The exposure of the site to wind is normal (not clouded). The texture of the ground is grass lawn with a surface solar and visible reflectance of 0.22. This means that the ground is not reflective.

Annual average outdoor air temperature of 29.05^oC and maximum difference in monthly outdoor temperature of 2^oC was used for the simulation. The simulation period used for the study is 1 year (12 months) from January to December 2016. Air temperature and relative humidity values were generated every 10 minutes.

Two 1000mm x 1000mm test cells were modelled in the design builder software. One as a control and the other with the green roof. The walls (control and experimental cells) were made of 20mm thick cement mortar render for both external and internal wall of 150mm sandcrete block and a mass concrete floor.

Two parameters, Leaf Area Index (LAI) and soil depth were considered in the scenarios generated to ascertain its impact on indoor temperature. Based on the soil depths that were considered for the simulation, both intensive and semi-intensive type of green roofs were considered as was informed by the work of Ahmed and Alibaba (2016). Moreover, the two factors were chosen because several studies (Beradi, 2016; Silva et al., 2016; Gagliano et al., 2015; Refahi and Talkhabi, 2015; Jaffal et al., 2012) have reported on them. Further, these factors have been reported to lead to different temperature reductions in different climatic areas (Yang et al. 2017; La Roche and Berardi, 2014). The latter pointed out that, depending on the local climate, both soil depth and leaf area index played different roles in affecting the peak cooling load.

After a series of 30 scenarios created using the LAI and substrate depth, eight tests were concluded on using 4 scenarios. Table 1 below illustrate the matrixes. For all the experiments, sandy loamy soil with water content of 12.5% is used.

Table 1: Simulated experiments involving four scenarios of leaf area index and substrate depths

TEST	SCENARIOS
1 & 2	LAI2 and 5 respectively, and Soil depth of 70-150mm
3 & 4	LAI5 and 2 respectively, and Soil depth of 200mm
5 & 6	LAI2 and 5respectively, and Soil depth of 300mm
7 & 8	LAI5 and 2 respectively, and Soil depth of 500mm

3 RESULTS AND DISCUSSION

The Tables and Figure shown below represent the findings from the simulation experiment. From Table 2 below, LAI5/70-150mm seems to perform slightly better than LAI2/70-150mm. As expected, the control values show the real case on the ground with June-August recording low values because of the rainy season in Ghana. A difference of 1.2°C and 1.5°C is recorded for LAI2/70-150mm and LAI5/70-150mm and the control respectively.

Table 2: Effect of LAI2/70-150mm and LAI5/70-150mm on mean temperature

SIMULATED MEAN INDOOR TEMPERATURE VALUES

TREATMENT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
LAI2/70-150mm	28.97b	29.45b	29.69b	29.51b	29.31b	27.44b	26.50b	26.47b	26.60b	27.38b	29.11b	28.85b
LAI5/70-150mm	28.60c	29.09c	29.30c	29.13c	28.92c	27.18c	26.28c	26.26c	26.34c	27.08c	28.79c	28.51c
CONTROL	30.23a	30.69a	30.93a	30.69a	30.64a	28.75a	27.74a	27.78a	27.84a	28.60a	30.34a	30.05a
LSD	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table 3: Effect of LAI2/200mm and LAI5/200mm on mean temperature

SIMULATED MEAN INDOOR TEMPERATURE VALUES

TREATMENT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
LAI2/200	28.65b	29.11b	29.32b	29.16b	29.95b	27.22b	26.31b	26.27b	26.36b	27.13b	28.81b	28.48b
LAI5/200	28.57c	29.05c	29.26c	29.11c	28.89c	27.11c	26.21c	26.20c	26.28c	27.05c	28.75c	28.48b
CONTROL	30.23a	30.69a	30.93a	30.69a	30.64a	28.75a	27.74a	27.78a	27.84a	28.60a	30.34a	30.05a
LSD	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

LSD – Least Significant Differences

From Table 3 above, January to November showed significant differences (P≤0.05) between the treatments where the least was recorded by LAI5/200mm and the control had the highest temperature values. December did not show significant differences between the treatments. Table 4 illustrates the findings for LAI2/500mm and LAI5/500mm.

Table 4: Effect of LAI2/500mm and LAI5/500mm on mean temperature

SIMULATED MEAN INDOOR TEMPERATURE VALUES

TREATMENTS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LAI2/500mm	28.65c	29.14b	29.32c	29.16c	28.95c	27.22b	26.31b	26.27b	26.36b	27.13b	28.81c	28.55c
LAI5/500mm	28.66b	29.10c	29.34b	29.18b	28.97b	27.13c	26.31b	26.20c	26.36b	27.13b	28.83b	28.57b
CONTROL	30.23a	30.69a	30.93a	30.69a	30.64a	28.75a	27.74a	27.78a	27.84a	28.60a	30.34a	30.05a
LSD	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

March, April and May portrayed significant differences (P≤0.05) between the treatments with the control showing relatively high temperature values. The least values were recorded by LAI2/500mm for the months of Jan, Mar-May, Nov-Dec. This observation followed a similar trend to the month of November and December. In the month of February, June and August, significant differences (P≤0.05) were achieved by the treatments with the lowest temperature values recorded by LAI5/500mm. In the months of January, July, September and October, significant differences were not showed by the treatments (P ≥0.05).

In Table 5, Jan, Mar-Jul indicated significant differences (P≤0.05) between the treatments where the least was recorded by LAI2/300mm. Similar observation is seen in the months of Sept, Nov-Dec. The observation was different in the months of Feb, Aug and Oct. where lower temperatures values were recorded by LAI5/300mm. Significant differences (P≤0.05) were achieved in these months. Figure 1 displays a graphical representation of all the scenarios against the control in terms of temperature reduction.

Table 5: Effect of LAI2/300mm and LAI5/300mm on mean temperature

SIMULATED MEAN INDOOR TEMPERATURE VALUES

TREATMENT	JAN	FEB	MAR	APR	MAY	JUNE	JUL	AUG	SEPT	OCT	NOV	DEC
LAI2/300mm	28.61c	29.13b	29.30c	29.15c	28.94c	27.07c	26.30c	26.28b	27.07c	28.78a	28.77c	28.52c
LAI5/300mm	28.66b	29.08c	29.33b	29.17b	28.96b	27.23b	26.32b	26.20c	26.37b	27.14c	28.83b	28.56b
CONTROL	30.23a	30.69a	30.93a	30.69a	30.64a	28.75a	27.74a	27.78a	27.84a	28.60a	30.34a	30.05a
LSD	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

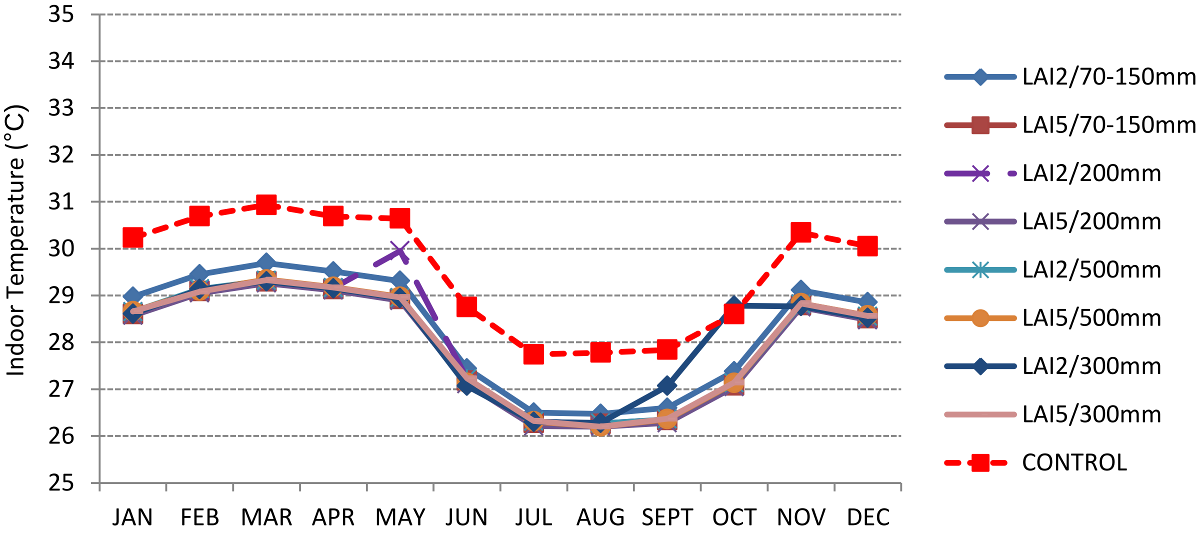

Figure 1: Scenarios considered in the test

In Figure 1 above, there is evidence that five of the scenarios performed better throughout the year. LAI5/70-150mm, LAI5/200mm, LAI5/300mm, LAI2/500mm and LAI5/500mm all achieved a 1.5°C difference when their averages were compared to that of the control. These results are comparatively better than that of the study reported by Qin et al. (2012) that showed that a green roof test bed in Singapore (China), can reduce the internal air temperature by an average value of 0.5°C when compared with a bare roof. In another work, a 2°C drop in summer internal air temperature by the installation of a green roof on buildings located in Athens was determined (Niachou, 2001). From this, conclusion can be drawn that indeed substrate depth and the plant characteristics (leaf properties) do affect the performance of the green roof and subsequently the indoor thermal performance (Bevilacqua, et al., 2015; Neda et al., 2015).

A critical look at the soil profiles showed that the deeper soil depths (200mm, 300mm and 500mm) get warm from midday to late evening (Sellers, 1965 and Carson, 1961) and the heat flux is stored for a longer time before it is gradually transmitted to the indoor space as it cools. Such indoor spaces are warmer than the shallow depths of 70-150mm as only 20% (Weng et al., 2004) of the solar radiation is transmitted to the soil. At a superficial depth, the heat is not stored for a longer time but is transfered gradually into the atmosphere and the indoor space. Investigations done by Berardi et al. (2014) suggested that, soil works as inertial mass with high thermal capacity and low thermal transmittance.

Wong et al. (2003), Emilsson et al. (2007), Wolf and Lundholm (2008) and Sun et al. (2013) argue that deeper vegetative roofs produce lower temperatures (heat gain and loss) and that they have a better thermal performance.The authors further suggested that 100mm increase in soil depth increases the thermal resistance of dry clay soil by 0.4m^2 KW. Berardi et al. (2014) suggested that the presence and quantity of water affects the thermal properties of the media. However, results from this study suggest that thinner depth of 70mm-150mm can also performs better in terms of temperature reduction if the LAI is broader. In the study of Yang et al. (2018) on “Green and cool roofs ’ urban heat island mitigation potential in tropical Climate”, net radiation was observed to have decreased compared to the conventional roof with smaller decrease for shallow soils and low LAI index and larger decrease for thicker soil layer and higher LAI value. This means that though its possible for a shallow soil (70-150) and a high LAI indexed plant to significantly cool indoors spaces, a thicker soil layer with a higher LAI value, should be considered for added advantages. Again having LAI5/70-150mm achieve the same reduction as the other deep soil depth confirms Jim and Tsang (2011) assertion that that thermal performance of green roof could be obtained with only 10cm soil. On the contrary, Nardini et al. (2012) in an experiment found out that significant differences in terms of rooftop temperature reductions was between 120mm and 200mm soil thickness. However, Sun et al. (2014) argued that the effect of soil thickness on green roof thermal performance was not linear. Although thick soil had a higher thermal resistance, it also could store more water at the bottom and limit the evaporation of soil surface.

CONCLUSION AND RECOMMENDATIONS

The study explored the effect of green roofs on the thermal performance of tropical buildings through a simulation experiment under the climate of Kumasi, Ghana. Plants and soil have been shown to play an important role in the performance of green roof systems and this study has shown that leaf Area Index (LAI) and soil depth are two of the most important factors when it comes to thermal performance of green roofs. Based on the simulation results, the following conclusions can be drawn:

1. That green roofs can maintain a noticeable lower indoor temperature values throughout the year.
2. With a larger LAI and a shallow soil depth, cooler conditions can still be achieved within the interior.
3. That notwithstanding, soil thickness does have a noticeable effect on the thermal performance of the green roof building. Four of the best performed scenarios all had substrate depth above 150mm.
4. As both LAI and soil depth increases above a certain threshold (LAI5/500mm), their effect deceases.
5. From the study it is noticed that either LAI is large or the substrate is deep, a significant reduction in temperature cannot be found. For instance LAI5/300mm, LAI2/500mm, LAI5/70-150mm all recorded an average reduction of 1.5°C less than the control.

The results of the study have shown the potential of green roofs, specifically, larger leaf area indices and substrate in reducing indoor temperature values. The underlying reason is the shading potential of the leaves. In tropical countries, shading continues to be shown in studies to be one of the key sustainable design measures to be considered in designing buildings. The decrease of 1.5°C when synergistically added to the positive effects of other measures such as wall shading or green walls, could lead to a more positive result. Future studies should holistically consider total shading to see the specific benefits of sustainable design recommendations. Architects and policy makers are advised on the strict adherence to positive guidelines to make spaces comfortable.

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