DETERMINING THE THRESHOLD FOR VARIATION IN INDOOR TEMPERATURE REDUCTION CAPACITY OF DIFFERENT GREEN ROOF DEPTHS IN HOT AND DRY CLIMATE

DETERMINAÇÃO DO LIMIAR DE VARIAÇÃO DA CAPACIDADE DE REDUÇÃO DA TEMPERATURA INTERNA DE COBERTURAS VERDES DE DIFERENTES PROFUNDIDADES EM CLIMAS QUENTES E SECOS

DETERMINACIÓN DEL UMBRAL DE VARIACIÓN DE LA CAPACIDAD DE REDUCCIÓN DE LA TEMPERATURA INTERIOR DE CUBIERTAS VERDES DE DIFERENTES PROFUNDIDADES EN CLIMAS CÁLIDOS Y SECOS

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Abstract. To forestall the dangers of overdesign, initial and maintenance costs, and unnecessary loading on the supporting roof, the study was primarily aimed at determining the significant difference in indoor temperature reduction capacity between various green roof models of varying thicknesses within the extensive green roof category. Using a contextualized substrate layer of 25mm as the difference in depth between green roof alternatives, the degree of thermal insulation for the interior was observed on six extensive green roof models of 50mm, 75mm, 100mm, 125mm, and 150mm thicknesses. This is to elucidate the level of significant differences in thermal efficiency between the models. EnergyPlus 8.3.0 simulation software was used to conduct a thermal performance survey on the sampled models. The temperature profiles of all the cases were collected and subjected to statistical analysis using SPSS V 21.0 to conduct an ANOVA and a proceeding Post hoc test to determine where the difference lies between the green roof groups. The results revealed that; no substantial difference in thermal performance exists between alternatives where the difference in depth is around the 25mm mark. Revealing that the threshold for any significant change in thermal insulation is denoted by a 50mm difference between alternatives. This research was carried out to facilitate the initial process of green roof selection, design, detailing, and specifications writing for architect engineers, and other stakeholders.

Keywords: Extensive green roof, Heat transfer, Thermal Insulation, Temperature Profile.

Resumo. Para evitar os perigos de superdimensionamento, custos iniciais e de manutenção elevados, e carregamento desnecessário sobre o telhado de suporte, o objetivo principal deste estudo foi determinar a diferença significativa na capacidade de redução da temperatura interna entre diversos modelos de telhados verdes de diferentes espessuras, dentro da categoria de telhados verdes extensivos. Utilizando uma camada de substrato contextualizada com uma diferença de profundidade de 25mm entre as alternativas de telhados verdes, observou-se o grau de isolamento térmico para o interior em seis modelos de telhados verdes extensivos com espessuras de 50mm, 75mm, 100mm, 125mm e 150mm. O objetivo foi elucidar o nível de diferenças significativas na eficiência térmica entre os modelos. O software de simulação EnergyPlus 8.3.0 foi utilizado para conduzir uma análise de desempenho térmico nos modelos amostrados. Os perfis de temperatura de todos os casos foram coletados e submetidos a uma análise estatística utilizando o SPSS V 21.0, com realização de um teste ANOVA seguido de um teste Post hoc para determinar onde residem as diferenças entre os grupos de telhados verdes. Os resultados revelaram que não existe uma diferença substancial no desempenho térmico entre alternativas onde a diferença de profundidade é em torno de 25mm. Foi identificado que o limiar para qualquer mudança significativa no isolamento térmico é marcado por uma diferença de 50mm entre as alternativas. Esta pesquisa foi conduzida para facilitar o processo inicial de seleção, projeto, detalhamento e especificação de telhados verdes para arquitetos, engenheiros e outros stakeholders.

Palavras-chave: Telhado verde extensivo, Transferência de calor, Isolamento térmico, Perfil de temperatura.

Resumen. Para prevenir los peligros del sobrediseño, los costos iniciales y de mantenimiento y la carga innecesaria en el techo de soporte, el estudio se dirigió principalmente a determinar la diferencia significativa en la capacidad de reducción de la temperatura interior entre varios modelos de techo verde de diferentes espesores dentro de la categoría de techo verde extensivo. Utilizando una capa de sustrato contextualizada de 25 mm como la diferencia de profundidad entre las alternativas de techo verde, se observó el grado de aislamiento térmico para el interior en seis modelos de techo verde extensivo de 50 mm, 75 mm, 100 mm, 125 mm y 150 mm de espesor. Esto es para dilucidar el nivel de diferencias significativas en la eficiencia térmica entre los modelos. El software de simulación EnergyPlus 8.3.0 se utilizó para realizar una encuesta de rendimiento térmico en los modelos muestreados. Los perfiles de temperatura de todos los casos se recopilaron y se sometieron a un análisis estadístico utilizando SPSS V 21.0 para realizar un ANOVA y una prueba post hoc para determinar dónde se encuentra la diferencia entre los grupos de techos verdes. Los resultados revelaron que; No existe una diferencia sustancial en el rendimiento térmico entre las alternativas donde la diferencia de profundidad es de alrededor de 25 mm. Se revela que el umbral para cualquier cambio significativo en el aislamiento térmico se denota por una diferencia de 50 mm entre las alternativas. Esta investigación se llevó a cabo para facilitar el proceso inicial de selección, diseño, detalle y redacción de especificaciones de techos verdes para arquitectos, ingenieros y otras partes interesadas.

Palabras-clave: Techo verde extensivo, transferencia de calor, aislamiento térmico, perfil de temperatura.

1. INTRODUCTION

Thermal insulation capabilities in the systems for green roofs rely on the planting composition and thermal mass of the substrate. However, regardless of the planting scheme, the thermal insulation capabilities of green roofs depend largely on the thickness of the growth media (Brocki, 2023; Peng & Jim, 2015); hence, the thicker the growth media, the better the thermal insulation prowess. Unfortunately, deeper substrates also translate to more weight of the system which is detrimental to the structural stability of the supporting roof (Salihu. 2021, Petreje, 2023; Dunnett & Kingsbury, 2004).

This is why green roof design and construction for any given project is a complex task that sometimes leads to pitfalls like the unnecessary cost of installation and maintenance, overdesign, and most crucially structural overburden on the roof system (Schweizer & Erell 2014; Rizzo, et al, 2023). It is thus necessary for green roof designers, architects, and engineers to design and select appropriate models in tune with project priorities as informed by the desired benefits of the system.

The major parameters considered in estimating green roofs' thermal performance involve the growth medium's type, thickness, density, and moisture content (Lambrinos, 2015; Barrio, 1998). As reiterated by Peng & Jim, (2015) and Morau, Rakotondramiarana, & Ranaivoarisoa, (2015); material compositions and thickness of the growth media have direct effects on plant performance and is therefore considered to be the most important component of the green roof

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

system. According to ASTM International, (2014); the growth media must be lightweight, readily available locally, have high drainage capabilities, and be able to contain water and nutrients while supporting plant life with minimal care input without leaching, and must not break down easily. Therefore, appropriate depth and materials must be chosen for any project. It is necessary to know the principal purpose any green roof project is designed to satisfy.

For instance, it has been established that green roof benefits like storm-water retention require deeper substrate composition than other benefits like acoustics and thermal insulation (Zhang, 2018; Yilmaz 2016;); conversely, according to the ASTM International (2014) a 25mm thickness in a green roof system is significant enough to sustain plant life and actualize the system's performance. However, this assertion can be regarded as location-specific due to variations in requirements to cater to challenges of inclement harsh weather, water retention, and plant sustenance that may demand the subscription for deeper substrates in hot climates (Schweizer & Erell, 2014; Dvorak, & Bousselot, 2021).

Typically, the common and popular extensive green roof thicknesses used are 50mm, 100mm and 150mm (Pettersson Skog et al. 2021; Besir & Cuce, 2017); however, for many locations like Nigeria, there is limited access to a locally established depository to developed value functions of green roof benefits (Salihu, 2021). It is therefore difficult to ascertain the threshold at which a significant change in thermal insulation may occur between the different models within the green roof types. For example, whether there is a significant difference in indoor temperature reduction between a 50mm-thick growth media and a 75mm-thick model or beyond.

As a designer, equipping oneself with such knowledge could facilitate in avoiding the problem of unnecessary cost and overdesign, where mistakes could be made in designing deeper substrates that do not offer any more value than the lighter and less costly shallow alternative. In that vein, the study sought to uncover the categorical difference in thermal performance between alternative thicknesses within the extensive green roof type.

The thickness used to delineate the different layers (thicknesses) of the green roof models under study is a 25mm depth, as affirmed by ASTM International (2014) to be the shallowest green roof thickness that can support plant growth. Subsequently, the question that needs to be addressed in this study is; at what change in depth of growth media can a significant difference in indoor temperature reduction capacity be observed within the outlined green roof alternatives? The research hypothesis for the study is also stated thus:

> *HO1. There is no statistically significant difference in indoor temperature reduction capacity between any 25mm change in growth media thickness within the outlined extensive green roof alternatives.*

2. Green Roof's Rudiments of Heat Transfer and Indoor Temperature Reduction

Green roofs can be defined as rooftops covered with growing medium, purposefully vegetated, and or spontaneously colonized by plants (Brocki, 2023; Catalano, Armando, Badalucco, & Guarino, 2018). The primary benefits of the green roof are its increased energy efficiency used in providing thermal comfort via cooling in the hot season and added insulation in

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

the winter (Mohapatra et. al., 2020). Longer roof membrane life, sound insulation, and the capacity to convert unused roof space into other kinds of building occupant amenity space are further advantages (Alim, 2022). Additionally, green roofs retain and purify runoff, filter the air, and open up new avenues for habitat development and biodiversity protection (Wooser, 2022).

A reduction in air pollution, the urban heat island effect, and aesthetics are some of the system's other intangible advantages (Dvorak & Bousselot, 2021; Mohapatra et al., 2020). On the other hand, green roofs are more expensive initially and require more upkeep than conventional roofs. This is because they use more energy to provide thermal comfort by cooling during the summer and adding insulation during the winter poses a great challenge in their general implementation (Polo-Labarrios, et. al., 2020).

Figure 1 shows the typical elements of a conventional structural support roof that are part of a green roof system. There are three main layers of plants in it: the substrate (growth medium), and the drainage layer also comprised of various accessories used for root barrier, waterproofing, and damp proofing (Mohapatra, et. al., 2020; Baciu 2020).

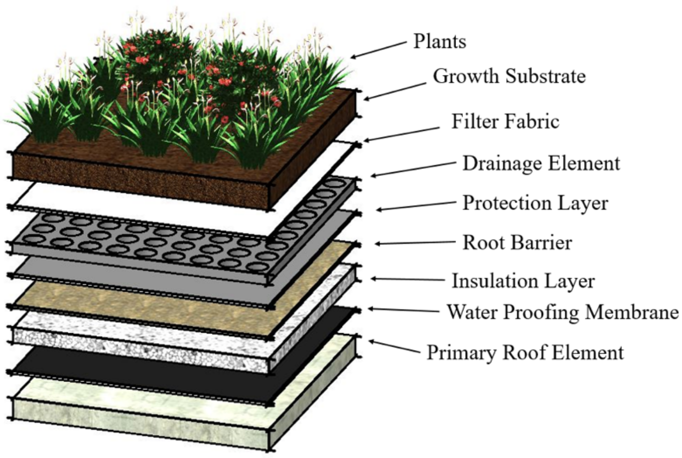

Figure 1. Schematic diagram of the layered structure of a typical green roof system

With differences in substrate layer weight and thickness, water requirements, plant choices, usefulness, and construction and maintenance costs, green roofs can be broadly divided into two types: extended and intense (Mihalakakou, et al., 2023). As illustrated in Table 1, Technically, the degree of maintenance is used to differentiate between these two systems, with intense green roofs being identified by a more rigorous maintenance schedule than their counterpart (Brocki, 2023; Skog Pettersson et al. (2021).

In contrast to intensive green roofs, which are often accessible and characterized by their deeper soil, higher weight, greater plant diversity, higher capital costs, and greater maintenance needs, extensive green roofs, which range in depth from 50 to 150 mm, are often unavailable (Mihalakakou, et al., 2023; Mohapatra, et. al., 2020). When elements of both extensive and intensive green roof types prevail, it is considered semi-intensive (Raji, Tenpierik, & Dobbelsteen, 2015; Mohapatra, et. al., 2020).

Table 1. Green roof classification usage, maintenance requirements, and construction factors

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

Classification Factors	Extensive	Semi-Intensive	Intensive
Maintenance	less	occasional	more
Water requirements	Nil	Occasional	Routinely
Vegetation type	Herbs, Grass, Fern	Shrubs, Small plants	Shrubs, Trees,
Cost	Less	Medium	High
Weight (kg/m2)	60–150	120–200	180–500
Utility	Protective covering	Designer vegetated roof	Recreational garden
build-up height (mm)	50–150	120–250	200–600

Evapotranspiration, shade, insulation layers, and thermal mass are all part of the intricate process by which a green roof reduces temperature. These elements have demonstrated a variety of beneficial thermal and energy performances in a range of climates and building types (He, et al. 2020; Cascone et al., 2019). As in all typically cases, heat transfer in green roofs occurs through conduction, convection, and radiation; however, apart from the conventional heat transfer mechanisms, the two major concepts studied in green roof heat transfer are evaporation and evapotranspiration (Becker and Wang, 2011).

Climate modification mechanisms experienced in the green roof are created by a raised albedo facilitated by the plant's leaves, and protection of construction materials against evapotranspiratory cooling and sunlight (Speak et al., 2013). Water evaporation by converting more of the inputs into latent heat when the shortwave solar radiation is absorbed by the building material and reradiated as longwave radiation at night, green roofs enable enhanced evapotranspirative cooling, which lowers the sensible heat flow (Speak, 2013).

In effect, therefore, vegetation on green roofs plays a vital role in heat transfer by providing shade, reducing solar radiation absorption, and promoting evapotranspiration. The parameter best desired in this regard is the According to Bernardi and Hoseini (2014), the leaf area index (LAI) is the ratio of the total upper leaf surface area to the land area on which the plants are cultivated. Plants with a low LAI are more suited for insulation in hot areas because it has been demonstrated that they withstand higher temperatures than those with higher indices and denser foliage cover. (Wong, Cheong, Yan, Soh, Ong, & Sia, (2003).

Figure 2 depicts the factors in the energy balance for a vegetated roof system, in which for this simple process significant reductions have consistently been recorded in the roof surface, ambient air, and indoor temperatures when green roofs are compared to conventional roofs (Hui, 2006; Cardoso, & Vecchia, 2013). By leveraging the cooling effect of vegetation, green roofs can significantly reduce energy consumption for cooling and create more sustainable and comfortable built environments.

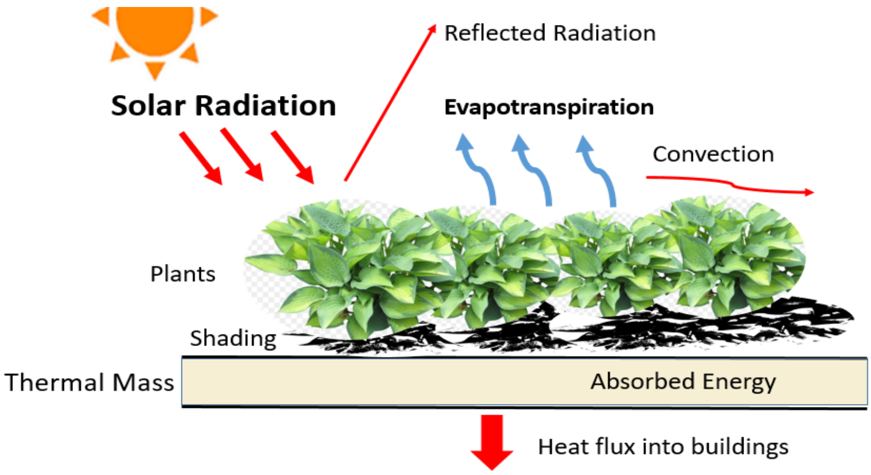

Figure 2. Green Roof Heat Flow.

Thermal Mass as provided by the substrate and vegetation, also plays a vital role in heat transfer in green roof systems. Materials with a high thermal mass have the ability to store heat during periods of solar radiation which prevents rapid temperature fluctuations; this helps to stabilise temperatures by absorbing and storing heat during the day and releasing it gradually at night (Langemeyer, 2020; Speak, et al, 2013).

Shallow green roof substrates with lesser thermal mass offer a considerable degree of thermal insulation in buildings; however, deeper substrates provide better insulation, resulting in significant energy savings, improved indoor comfort, and better environmental performance (Du, Arndt, & Farrell, 2018). Therefore, selecting an appropriate substrate depth is crucial for optimizing the thermal performance of a green roof based on specific climate conditions and project goals.

3. MATERIAL & METHODS

Quantifying the thermal and energy benefits of green roofs frequently requires experimental evaluations and/or simulation studies due to the intricacy of heat transmission in the layers of the roof components and the wide range of roof types (Polo-Labarrios et. al., 2020).

However, due to limited resources and difficulty in accessing specific live green roof samples required for this study, this research adopts the use of simulation using EnergyPlus 8.3.0. This was validated in a subsequent study by Salihu, (2021).

Although the green roof system comprises many layers, this study is mainly focused on the various thicknesses of the growing media as the independent variables for in-depth study. In this regard, the dependent variables that define the scope of evaluations are:

- The temperature profile of the studied thermal zones.
- Indoor temperature reduction capacity of the green roof alternatives.
- Threshold for change in indoor temperature reduction between the outlined growth media.

The green roof model adopted is featured in Salihu, Salisu, & Tukur. (2020), where a field survey was conducted using a 100mm-thick growing medium with a 3:1:1 mix ratio of ma-

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

sonry debris, loamy soil, and compost respectively; the plant of choice was Kalonchoe Integra of 150mm height. A combination of experimental and simulation approaches was used to conduct the validation study adapted from the IEA BESTEST, as forwarded by Haves, Judkoff, New, and Muehleisen, (2015).

After subjecting the obtained temperature profile to a correlation study using SPSS V.21, the results confirmed that there is a strong and positive correlation between readings in both simulated and field observation. Therefore, the data was deemed to be normally distributed, and that the difference between the two data sets was valid and can be used for further tests on the major exercises of this study.

A green roof model replicating the validated cases was thereafter replicated in the simulation software for further analysis. The cases studied are, the base case (bare roofed structure) labelled as GR0 for relative comparisons, the 50mm alternative labelled GR50, and the 75mm alternative labelled as GR75. Other cases are the 100mm, 125mm and 150mm labelled GR100, GR125 and GR150 respectively.

3.1. **Geometry**

The building selected for the study is a three-bedroom bungalow from the National Housing Program (NHP) 2017, by the federal government of Nigeria. The building was selected because it is an embodiment of the predominant architectural style of the location. It was built with the most conventional building materials, construction techniques and space allocation in tune with the stipulations of the National Building Code (NBC), 2006.

A model of the selected building was thereof developed and installed with a green roof system as shown in Figures 3 and 4. Subsequently, it was duplicated for manipulations to depict the outlined green roof alternatives outlined for scrutiny. Configuration of the entire model in walls, floors, ceiling, openings and support roof system was kept precisely the same, except for the green roofed cases where various green roof systems were installed upon the support roofs.

Values of the structural and thermal properties of the materials used are in line with the BEEC, (2017). Primary reference on material properties was also made extensively to studies of Poptami, (2014); Hegazy, Dabaieh, Wanas, Amer, & Johansson, (2016); Kim, Hong, & Koo, (2012). These materials and their properties are elaborately shown in Table 2.

Figure 3. Front Elevation. Source: NHP, 2017

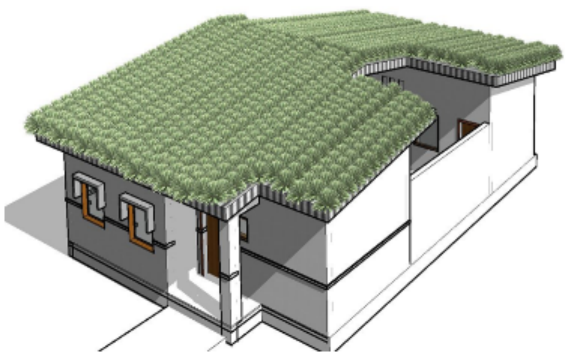

Figure 4. 3D view of the reference building with the installed green roof. Source: Field Survey

Br. J. Ed. Tech. Soc, v.17, n.se4, p.154-169, 2024
DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

Table 2. Simulation Input Parameters; Structure/Material properties.

	PARAMETER	ELEMENT	INPUT/PROPERTIES					
1	Location	Location template	Sokoto, Nigeria					
		Weather data	NGA Sokoto MNG (hourly weather data)					
2	Activity	templet	Domestic bedroom					
		occupancy	Dwell_DomBed Occ					
3	Construction	Building Element	Composition Description	Material Component	Size mm	R-Value	U-Value W/M2.K	Density (kg/m3)
		Bldg Area	3.5x3.5m		12.25m2			
		Walls	wall/plaster		230mm, 1.60 W/M2.K, 2100 kg/m3			
		Floor	Screeded	Mass Conc.	100mm, 1.75 W/M2.K, 2400 kg/m3			
		ceiling	Single Layer	Hard Board	5mm, 0.03 W/M2.K			
		windows	Sliding	Aluminium	205WWR			
		glazing	glazing	Clear glazed	5mm, 1.04 W/M2.K			
		Roof area			102m2			
		Support Roof	Roof cover	Aluminium	0.55mm, 1.25 W/M2.K			
			Tray	Aluminium	0.55mm, 1.25 W/M2.K			
		Green roof	Growing Medium	Gravel/Soil	1:1:3, 50mm-150mmthick, 0.32 W/M2.K			
			Plant	Succulent	150mm, 2.7LAI			
3	Lighting		Best practice template; normalised density 6 W/M2					
	HVAC		Fan coil unit with district cooling template (23w/m2)					
5	Natural Vent.							
6	Simulation Inputs and Output Options	Simulated Hrs	8760.00 hrs					
		Sim. Period	One year (1st January To 31st December)					
		Output Intervals	Hourly, Monthly summary					
		Output Data	Surface heat, Environmental, comfort parameters and energy					

3.2. **Simulation Exercise and Hypothesis Testing**

Energyplus Version 8.3.0 was used as a simulation engine for the main evaluations. To avoid a cumbersome and unnecessary process of simulation exercise the study opted to focus on the worst-case scenario as recommended by Kazman, and Klein (2002). Therefore, within the hot and dry climate region of Nigeria, Sokoto happens to be the location that records highest annual temperature averages. Records on rainfall also show that although it has slightly higher records in rainfall than other locations in the region, it also has a lower record of precipitation during the wettest months of the year.

Therefore, it was selected to represent the worst-case scenario within the hot-dry climate. The Sokoto weather file was thus used to perform all the outlined simulation exercises and assessments across the selected green roof samples delineated for the study. Typical weather

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

data used was Typical Meteorological Year (TMY) for EPW format; obtained from Weather Analytics, which is an affiliate of Energy Efficiency and Renewable Energy (EERE).

The result of the Annual Building Utility Performance Simulation (ABUPS) was collected from the tabular output report of the simulation timestamp. The temperature records were extracted on an hourly basis, which expressed the daily temperature characteristics of the roof systems. To test the proposed hypothesis, the simulation results were subjected to statistical analysis using SPSS V 21.0 to conduct an ANOVA, and a proceeding Post hoc test to determine where the difference lies between the green roof groups.

4. FINDINGS & DISCUSSIONS

4.1. Temperature profile of the green roof alternatives

Figure 5 shows the annual indoor temperature record of the studied bare roof and all the green roof alternatives. Consistent with the change in thickness of alternatives, the trend in change of higher indoor temperatures recorded decreased in favour of the alternatives with deeper growth media over their shallower counterparts within the set.

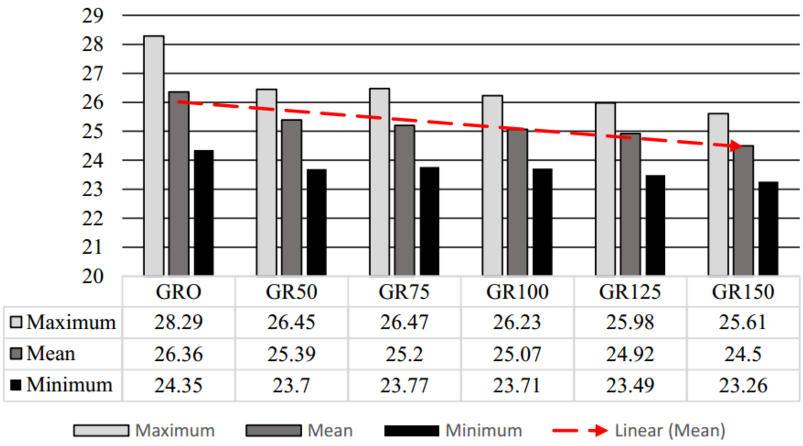

Figure 5. Maximum, mean and minimum Annual Indoor Temperature Record of GR0 and the alternative green-roofed cases.

As also shown in Figure 6, it was observed that; the maximum zone air temperatures for all the studied cases were recorded in April, May and June. While the minimum was in January and December. Average temperatures recorded were in March, July, August and September.

GR0 recorded the highest values in the data set, which elaborately shows the significant outlaying change in values due to the absence of green roof insulation. The lowest recorded temperature values were on the GR150, while the least reduction was found in the GR50 in contrast to higher values of the GR0.

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
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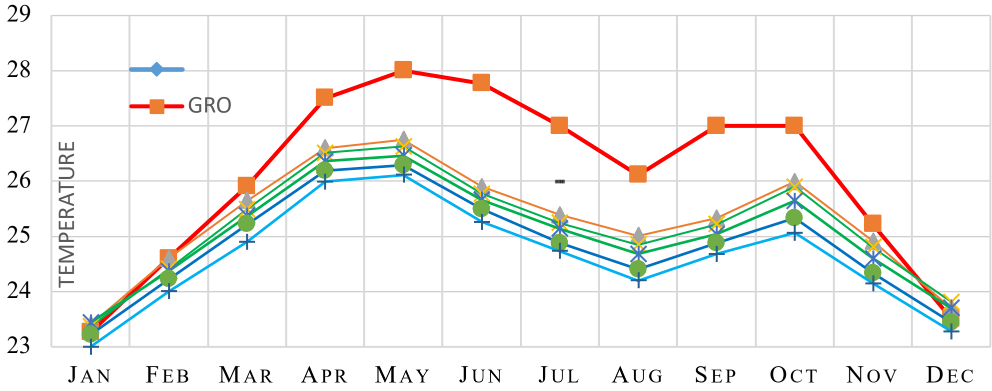

Figure 6. Annual temperature ranges of GR alternatives.

4.2. **Inferences from Records of the Temperature Profile**

To illustrate the difference in the thermal insulation delivered by each alternative, Figure 7 shows the trend of annual temperature ranges of the GR0, GR50 (shallowest alternative) and GR150 (deepest alternative). It also shows a typical green roof's behaviour towards providing thermal insulation for the interior as against the base-case scenario.

This is illustrated by the presence of a wider distance between the Outside DBT and the green-roofed cases over the GR0. As shown in the illustration, a wider distance, in this case, connotes better insulation from the higher outside temperature.

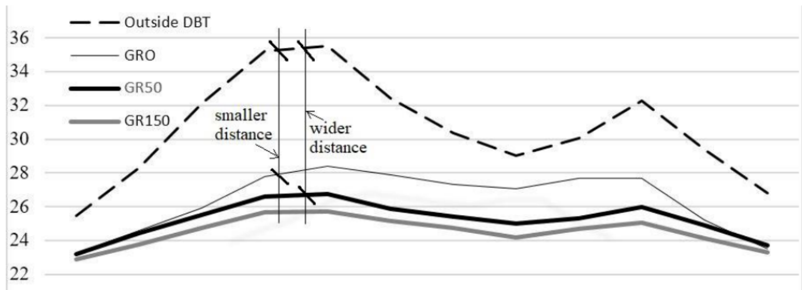

Figure 7. Level of thermal insulation between GR0, GR50 and GR150.

Figure 8 illustrates the annual rate of thermal insulation observed in the green-roofed alternatives. It is represented as the difference between the mean value recorded in the GR0 and the evaluated green-roofed alternatives. Table 3 also ruminatively shows the daily, monthly, seasonal and annual rates of thermal insulation offered by the different green roof alternatives over the bare roofed case.

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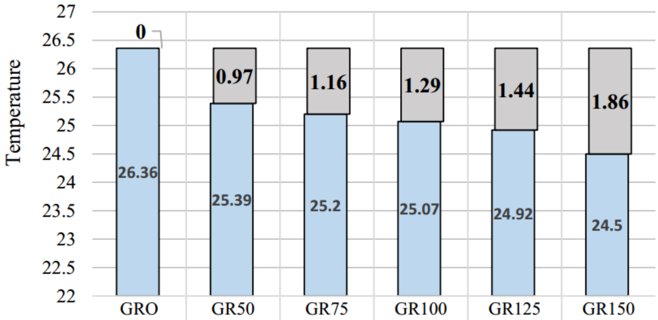

	GRO	GR50	GR75	GR100	GR125	GR150
Mean Difference	0	0.97	1.16	1.29	1.44	1.86
Mean	26.36	25.39	25.2	25.07	24.92	24.5

Figure 8. Rate of mean annual temperature reduction offered by the green roof alternatives over the bare roofed case.

Table 3. Rate of Thermal Insulation Offered by the Green Roof Alternatives; Source; Survey, 2024

Observed Record (Avr)	Roof Types GR0	GR50	GR75	GR100	GR125	GR150	Remark
Hottest day (C⁰)	30.08	27.67	27.65	27.63	27.61	26.50	
Difference (GR0)	0	2.41	2.43	2.45	2.47	3.58	**+ve Insulation**
(ODB, 35.53)	5.45	-	-	-	-	-	
Coldest day (C⁰)	20.78	21.16	21.13	21.11	21.10	21.08	
Difference -Day	0	0.38	0.35	0.33	0.32	0.30	**+ve Insulation**
Difference -Night		0.67	0.78	0.81	0.87	0.92	**+ve Insulation**
Hottest month (C⁰)	28.38	26.75	26.63	26.46	26.10	25.74	
Difference	0	1.69	1.75	1.92	2.28	2.64	**+ve Insulation**
Coldest month (C⁰)	23.26	23.31	23.47	23.54	23.62	23.90	
Difference	0	0.05	0.21	0.28	0.36	0.64	**+ve Insulation**
Annual	26.36	25.39	25.20	25.07	24.92	24.50	
Difference	0	0.97	1.16	1.29	1.44	1.86	**+ve Insulation**

All records are presented in averages and it shows that:

1. Positive insulation was recorded during the hottest day of the year. Where the ODB was 35.53°C, the bare roofed thermal zone recorded 5.45°C reduced indoor temperature. However, the GR50 with the lowest record of insulation recorded a 2.41°C reduction of indoor temperature, and GR150 being the thickest alternative recorded a 3.50°C reduction in indoor temperature.
2. Coldest day of the year; the green roofs recorded slightly warmer temperatures during the night than during the day all year round. The highest insulation was recorded in GR150 with 0.92°C.
3. The hottest month; 2.64°C reductions in indoor temperature was offered by the GR150. However, this reduced regressively from GR 125 to GR50 with 2.28°C, 1.92°C, 1.75°C and 1.69°C correspondingly.
4. Annual record; the recorded differences from the 26.36°C mean annual value of the GR0 were, 0.97°C for the GR50, 1.16°C for GR75, 1.29°C for the GR100 alternative, 1.44°C for the GR125 and 1.86°C for the GR150.

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

4.3. **Test of hypothesis; threshold for variation in indoor temperature reduction**

The result confirmed that there is a high statistical difference between the control group (GR0) and the alternative groups. The highest mean difference was recorded on GR150 with 4.78, while the lowest was on GR50 with 3.07.

Within the green roof alternatives, the result from the ANOVA showed that the level of significance was 0.01 between groups. This denoted a statistically significant difference between all the levels of independent variables; however; to be able to determine where the difference lies, a Posthoc test was also conducted between the green roof groups.

The level of significance (>0.05) was recorded between groups, and the results of the test conducted showed that:

1. There is a statistically significant difference between GR75 to GR125 and GR50 to GR150 alternative groups.
2. There is also a statistically significant difference between GR75 to GR125 and between GR75 to GR150
3. GR100 has no statistically significant difference to GR50, GR75 and GR125, but it has a significant difference with GR150
4. GR125 has no significant difference with GR150 and GR100 alternatives, but it has a significant difference with GR75 and GR50.
5. GR150 bears no significant difference to GR125 but has a significant difference to GR50, GR75 and GR100 alternatives.

Figure 9 illustrates the pattern in the level of significance between alternatives; where the darker shade in cells denote a higher level of significance, and the lighter cells denote a weak significance. The red cells on the table conversely represent non-significance between groups.

Green Roof Alternatives (0.05 level)						
	GR0	**GR50**	**GR75**	**GR100**	**GR125**	**GR150**
GR0						
GR50			1.000	.999	.033	.002
GR75		1.000		.999	.029	.001
GR100		.999	.999		.078	.005
GR125		.033	.029	.078		.919
GR150		.002	.003	.005	.919	

Legend	
V. High	
High	
Average	
Low	
V. Low	
None	

Figure 9. Graphical representation of significant level between green roof alternatives

Based on the observations, it can be deduced therefore that; where the difference between options is 25mm in thickness, no significant difference in thermal performance was observed. The threshold for significant change in thermal insulation therefore is denoted by a 50mm difference (two thicknesses of 25mm) between alternatives for a significant difference to be attained. Indicating that if thermal insulation is the primary benefit of embarking on a green roof design, it requires 50mm thickness between alternatives to achieve a significant change in thermal insulation.

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

Meaning that a 100mm depth of substrate offers no significant change in insulation over a 125mm-deep substrate, and that the significant difference can only be obtained with a 150mm alternative as the case implies. Otherwise opting for any 25mm added depth can be regarded as over design and additional weight and cost to the system.

5. CONCLUSIONS & RECOMMENDATION

An outline of the commonest depths of extensive green roof alternatives were evaluated to attain a categorical conclusion of their indoor temperature reduction capacity. The samples were subjected to a simulation exercise and the results revealed a consistent outcome with what is obtained in the literature review and ongoing research.

It proved that, with any significant change in thickness of green roof alternatives, the trend in change of higher indoor temperatures decreases in favour of alternatives with deeper growth media over the shallow alternatives. Results also affirmed that the same progressive positive insulation was recorded during the hottest and coldest times of the year. However, the main thrust of the study is not only focused on uncovering the level of significance in indoor temperature reduction each change in depth of growth media offers; it is posed at uncovering the threshold at which that significant change occurs between the alternatives.

A hypothesis was posed to answer the core question of the study which stated thus; there is no statistically significant difference in indoor temperature reduction capacity between any 25mm change in growth media thickness within the outlined extensive green roof alternatives. This assertion was held to be true, as statistical analysis revealed that there has to be at least a difference of 50mm between the alternative layers of a green roof to attain a significant difference in its thermal performance. Therefore, with a difference of 25mm, no significant difference in thermal performance was observed between any green roof alternative and its immediate counterpart within the outlined extensive green roof options being studied in the hot dry climate of Nigeria.

As earlier iterated, to avert the threats of overdesign, initial and maintenance costs, and avoidable loading on the supporting roof, this study is instrumental in disseminating valuable information to green roof designers, engineers, and developers. It will also assist in facilitating an appropriate green roof selection strategy for any project where indoor temperature reduction benefits of green roofs are the primary objective.

REFERENCES

Alim, M. A., Rahman, A., Tao, Z., Garner, B., Griffith, R., & Liebman, M. (2022). Green roof as an effective tool for sustainable urban development: An Australian perspective in relation to stormwater and building energy management. Journal of Cleaner Production, 362, 132561.

American Society for Testing and Materials (ASTM E 2400) 2014. Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems. ASTM International, West Conshohocken, PA, 4. Energy and Buildings., 115, 411–428.

Baciu, I. R., Taranu, N., Isopescu, D. N., Lupu, M. L., Dragan, T. C., & Maxineasa, S. G. (2020, March). Green roofs–modern solutions for greening buildings. In IOP Conference Series: Materials Science and Engineering. Vol. 789, No. 1, p. 012001. IOP Publishing.

Barrio, E. P. D. (1998). Analysis of the green roofs cooling potential in buildings. Energy and Buildings. Volume 27(2), pp179-193. Retrieved from https://www.researchgate.net/publication/223880039

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907

Becker, D., and Wang, D. (2011). Green Roof Heat Transfer and Thermal Performance. (Unpublished Master's Thesis) Mellon University, Carnegie. The United States. Retrieved from https://iglcstorage.blob.core.windows.net/papers/attachmenta0281368-3309-4474-9abf-fcfc56b9f8d9.

Berardi, U., and G. Hoseini, (2014). State-of-the-art analysis of the environmental benefits of green

roofs. Energy and Buildings. Retrieved from journal homepage: www.elsevier.com/locate/enbuild, 115, 411–428.

Besir, A. B., & Cuce, E. (2018). Green roofs and facades: A comprehensive review. Renewable

and Sustainable Energy Reviews, 82, 915-939.

Catalano, C., Armando, V., Badalucco, L., and Guarino, R. (2018). Some European green roof norms and guidelines through the lens of biodiversity. Ecological Engineering, 115(October 2017), pp15–26. https://doi.org/10.1016/j.ecoleng.2018.01.006

Cascone, S. (2019). Green Roof Design: State of the Art on Technology and Materials. Sustainability. Volume 11/3020. Pp 2-28. Retrieved from https://doi.org/10.3390/su11113020 on 22/10/2021 doi:10.3390/su11113020

Cardoso, T.G., and Vecchia, F. (2013). Thermal Behavior of Green Roofs Applied to Tropical Climate. Journal of Construction Engineering, (2), pp1–7. https://doi.org/10.1155/2013/940386

Du, P., Arndt, S. K., & Farrell, C. (2018). Relationships between plant drought response, traits and climate of origin for plant selection. Ecological Applications. Volume 28(7), pp. 1752–1761 https://doi.org/10.1002/eap.1782

Dunnett, N. and Kingsbury, N. (2004). Planting Green Roofs and Living Walls.: Timber Press,

Portland.

Dvorak, B., & Bousselot, J. (2021). Theoretical development of ecoregional green roofs. Ecoregional Green Roofs: Theory and Application in the Western USA and Canada, 41-79.

Haves, P., and Berkeley, L. (2017). Validation and Uncertainty Characterization for Energy Simulation. 2017 Building Technologies Office Peer Review, US Department of Energy. Lawrence Berkeley National Laboratory.

He, Y., Yu, H., Ozaki, A., & Dong, N. (2020). Thermal and energy performance of green roofs and Cool Roof: A comparison study in Shanghai area. Journal of Cleaner Production, 267.

Hegazy, A., Dabaieh, M., Wanas, O., Amer, M., and Johansson, E. (2016). Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings Reducing cooling demands in a hot dry climate. Energy and Buildings. 89, 142-152. DOI: 10.1016/j.enbuild.2014.12.034

Hui, S. C. M. (2006). Benefits and potential applications of green roof systems in Hong Kong. Proceedings of the 2nd Megacities International Conference 2006.

Guangzhou China. pp. 351-360. Retrieved from http://hdl.handle.net/10722/100487

Kazman, R., and Klein, M. (2002). Making Architecture Design Decisions: An Economic Approach. Carnegie Mellon University.

Kim, J., Kim, J., Hong, T., and Koo, C. (2012). Economic and Environmental Evaluation Model for Selecting the Optimum Design of Green Roof Systems in Elementary Schools. Environmental Science & Technology. volume 46, pp8475−8483. https://doi.org/10.1021/es2043855

Lambrinos, J.G., (2015). Green Roof Ecosystems, Ecological Studies, Analysis and Synthesis. vol. 223. Springer.

Langemeyer, J. Wedgwood, D. McPhearson, T. Baró, F. Madsen, A.L. Barton, D.N. (2020). Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona, Sci. Total Environ. 707 (2020) 135487, https://doi.org/10.1016/j.scitotenv.2019.135487.

Mihalakakou, G., Souliotis, M., Papadaki, M., Menounou, P., Dimopoulos, P., Kolokotsa, D., & Papaefthimiou, S. (2023). Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives. Renewable and Sustainable Energy Reviews, 180, 113306.

Mohapatra, S., Verma, S., Chowdhury, S., Dwivedi, G., & Harish, V. S. K. V. (2021). A critical appraisal of green vegetated roofs: Energy and environment in focus. Materials Today: Proceedings, 46, 5703-5710.

Morau, D., Rakotondramiarana, H. T., and Ranaivoaarrisoa, T. F. (2015). Dynamic Simulation of the Green Roofs Impact on Building Energy Performance, Case Study of Antananarivo, Madagascar. 2nd International Conference on Advances in Energy Engineering (ICAEE. Pp 497–520. https://doi.org/10.3390/buildings5020497

National Building Code (2006). Ministery of Housing and Urban Development Federal Republic of Nigeria National Building Code. First edition. LexisNexis. Johannesburg, South Africa Peng, L. L. H., and Jim, C. Y. (2015). Seasonal and diurnal thermal performance of a subtropical extensive green roof: The impacts of background weather parameters. Sustainability Switzerland. Volume 7(8), 11098–11113. https://doi.org/10.3390/su70811098

Pettersson Skog, A., Malmberg, J., Emilsson, T., Jägerhök, T., & Capener, C. M. (2016). Gröna takhandboken: växtbädd och vegetation.

Petreje, M., Sněhota, M., Chorazy, T., Novotný, M., Rybová, B., & Hečková, P. (2023). Performance study of an innovative concept of a hybrid constructed wetland-extensive green roof with growing media amended with recycled materials. Journal of Environmental Mgt, 331, 117151

Polo-Labarrios, M. A., Quezada-García, S., Sánchez-Mora, H., Escobedo-Izquierdo, M. A., & Espinosa-Paredes, G. (2020). Comparison of thermal performance between green roofs and conventional roofs. Case Studies in Thermal Engineering, 21, 100697.

Poptani, H. (2014). Extensive Green Roofs: Potential for Thermal and Energy benefits in buildings in central India. 30th International Plea Conference 16-18 December 2014, CEPT University, Ahmedabad. pp 1–8. Retrieved from https://www.researchgate.net/publication/281551485_Extensive_Green_Roofs_Pot ential_for_Thermal_and_Energy_benefits_in_buildings_in_central_India

Raji, B., Tenpierik, M. J., and van den Dobbelsteen, A. A. J. F. (2015). The impact of greening systems on building energy performance: A literature review. Renewable and Sustainable Energy Reviews. Volume 45. pp610-623. DOI: 10.1016/j.rser.2015.02.011

Rizzo, G., Cirrincione, L., La Gennusa, M., Peri, G., & Scaccianoce, G. (2023). Green roofs' end of life: a literature review. Energies, 16(2), 596.

Salihu, M.M. (2021). A Framework for Green Roof Design Optimised for Reduction of Cooling Load for Residential Buildings in the Hot-Dry Climate of Nigeria (Unpublished PhD Thesis). Department Of Architecture, Faculty of Environmental Design, Ahmadu Bello University, Zaria, Nigeria.

Salihu, M.M., Salisu, A. S. and Tukur R. B., (2020). A Field Study on Thermal Insulation Performance of Green Roof in Buildings of Hot Dry Climate of Zaria, Nigeria. Journal of Environmental Studies. VOL. 4 issue 11 pp 14-24 ISSN 1110- 457X

Schweitzer, O., and Erell, E. (2014). Evaluation of the energy performance and irrigation requirements of extensive green roofs in a water-scarce Mediterranean climate. Energy and Buildings. Volume 68. Pp 25–32. http://dx.doi.org/10.1016/j.enbuild.2013.09.012

Speak, A. F. (2013). Quantification of the Environmental Impacts of Urban Green Roofs. (Unpublished PhD Thesis). The University of Manchester. The United Kingdom.

Speak, A.F. Rothwell, J.J. Lindley, S.J. Smith, C.L. (2013). Reduction of the urban cooling effects of an intensive green roof due to vegetation damage, Urban Clim. 3 (2013) 40–55, https://doi.org/10.1016/j.uclim.2013.01.001.

Zhang, Z. Szota, C. Fletcher, T.D. Williams, N.S. Werdin, J. Farrell, C. (2018). Influence of plant composition and water use strategies on green roof stormwater retention, Sci.Total Environ. 625 (2018)

775–781.

Yilmaz, D., Sabre, M., Lassabat` ere, L., Dal, M., Rodriguez, F., 2016. Storm water retention and actual evapotranspiration performances of experimental green roofs in French oceanic climate. Eur. J. Environ. Civ. Eng. 20 (3), 344–362.

Wong, N. H.; Chen, Y.; Ong, C. L.; Sia, A. (2003) Investigation of Thermal Benefits of Rooftop Garden in the Tropical Environment. Building and Environment. 38(261), 78-89

Wooster, E. I. F., Fleck, R., Torpy, F., Ramp, D., & Irga, P. J. (2022). Urban green roofs promote metropolitan biodiversity: A comparative case study. Building and Environment, 207, 108458.

DOI http://dx.doi.org/10.14571/brajets.v17.nse4.154-169
ISSN 2316-9907