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Field evaluation of indoor microclimates of green and bare roofed urban buildings at no-ventilation condition in a sub-Saharan climate

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Abstract: There is a growing use of green roofs on urban buildings around the world with a focus on reducing energy consumption of buildings. Energy consumption of buildings results mostly from heating or cooling of indoor spaces. When mechanical air conditioners are operating, windows (natural ventilation) are shut. This paper studied 2 field models, one with a living green roof and the other left bare (conventional), both without any sensible or latent heat loss or gain via their ventilation systems. Microclimatic data was collected at the field for the 2 rooms for a period of 25 days. Two microclimate parameters, air temperature and relative humidity which determines the highest effect on indoor thermal comfort were compared for the two models and with the ambient conditions. Result shows that both air temperature and relative humidity of the room with the green roof were lower than the bare roofed house. Fluctuations were also minimal for the green roofed urban building.

Keywords: Green Roof, Bare Roof, Evaporative Cooling, Cooling Loads, Building Energy

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1. Introduction

Contemporarily, air conditioning systems is the most widely used artificial type cooling system, albeit they have great energy expenditure [1]. Heating, ventilating and air conditioning (HVAC) systems in commercial buildings account for a large proportion of electricity bills for the buildings [2]. It is important to mention that cooling is four times the cost of heating a building. In developed countries, it accounts for around half of primary energy usage [3]. Generally, about one third of energy consumption in the world is attributed to buildings. The need for air conditioning arises due to heat gains from sunlight and electric lighting-which causes high temperature in rooms-unless windows are opened to allow natural air ventilate the place [4]. The implication of open windows is, other unwanted comfort levels might be reached such as draughts caused by wind, noise, dirt and odours that can flow in, hence, making the place uncomfortable.

Optimized selection of building materials for making the external envelop plays an important role in achieving thermal comfort in buildings, where thermal comfort is achieved through passive cooling strategies [5]. However, current practices in construction of buildings have seen a paradigm shift in the construction materials used. Lightweight construction materials are constantly being preferred over conventional heavy materials. The effect of these on the inner microclimate is that the slim thickness of the materials raises concern over the internal comfort conditions due to lack of thermal storage properties resulting in rapid swings of indoor temperature [5]. Frequent fluctuations of indoor condition makes controlling the conditions much more difficult and energy consuming for air conditioners.

Roofs present a very high fraction of the exposed urban area [6]. Given that the available free ground area in urban environments is quite limited and of very high economic value, it is relatively difficult to implement large scale mitigation technologies on ground surfaces of cities. At the same time, urbanization decreases the proportion of spaces dedicated to plants and trees or other mitigation infrastructures because of new building developments [7 as cited in 6]. On the contrary, roofs provide an excellent space to apply mitigation techniques, given that the relevant cost is limited, while the corresponding techniques are associated to important energy savings for the buildings.

The use of green roofs dates back to centuries ago [8]. However, they were not used to modify or insulate buildings then, but as a protective cover to prolong the life cycle of roofs. A green roof constitutes a layered structure of waterproofing membrane, growing medium and the vegetation layer itself [4, 8, 9]. More generally, it refers to any type of roof that a green technology has been incorporated with [10]. Due to their ability to reduce the proportion of solar radiation that reaches the roof beneath [3] and subsequent penetration into the building, they possess the potential to reduce the energy [10, 11, 12] that would have been used in cooling the higher heated spaces.

The need to evaluate the effects of greening without any ventilation systems is due to the fact that a high percentage of energy load of buildings is through ventilation systems [12]. Heat gain or loss in this experiment was strictly via the opaque building envelope. This research was also necessitated by the fact that building energy reduction is climate specific [6]. Thus, the absence of studies addressing issues mentioned above in sub-Saharan Kenya necessitated the need for this study.

2. Materials and Methods

2.1. Experimental Set-Up

Figure 1. *The two field models used for the experiment.*

Two rooms similar to an urban house were erected in order to measure microclimatic data used for the study. During the first period of the research, the roof of one room was entirely covered with a living green roof, while the other was left entirely bare. The living green roof comprised of a species of Mesembryanthemum plant found in Nairobi, Kenya. After a month of observation, the green roof was interchanged between the two models. This was done because of the location of the models in the surrounding. See Fig. 1 for an image of the field models built next to each other. One of the room was closer to an office building while the other enjoyed more space round the perimeter. This effect was thought to affect the air flow within the field models and therefore could obstruct wind flow for one model or cool the other model faster.

2.2. Location of the Study

The field experiments were located at Jomo Kenyatta University of Agriculture and Technology, Juja campus, Kenya, which represented an urban like area, complete with paved areas, concrete buildings and asphalted roads. The place is located in Central Kenya, an equatorial high altitude region on latitude 1° 11’ 00” S and longitude 37° N 07’ 00” with an altitude of 1728m (5672ft) above sea level [13].

The two models were located between two blocks, about 5 metres and 10 metres from each office block. There is about 5 metres of space between the two models. The landscape of the models was partially covered with a native Elephant grass. One model served as the model under observation, while the other served as the control. After a month collection of data, the roles between the two models were switched in order to assess whether the influence of one of building’s proximity to the other building had a significant effect or not.

2.3. Model Description

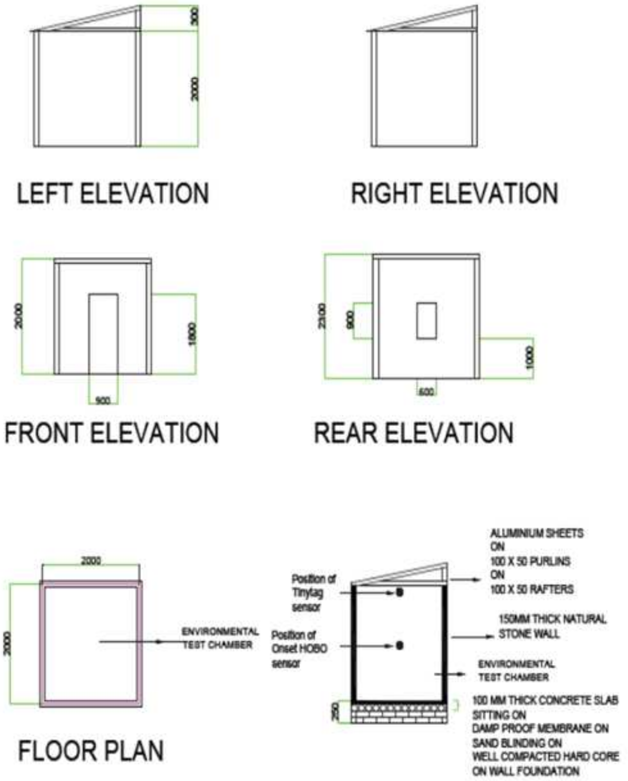

Figure 2. *AutoCAD drawing of the field models constructed.*

Two rooms of the same geometric and material properties were constructed. Stones, which are commonly found and used for construction within the area, were used to build the models. The foundation was 100mm deep without any column footings. The floors of the rooms were decked with marrum, stone ballast and thereafter a fine finish of cement mortar was applied on the surface. Polyethylene was used below the floors and around the perimeter of the floor to prevent moisture rise in the rooms. The inside wall surfaces, with the exclusion of the outside surfaces, were finished with cement mortar. A conventional roof was made, slanting in one direction, about 26°, covered with gauge 30 aluminum roofing sheets. There was a single door and window for each model, located in opposite direction. The door was made with timber while a single glazing window was used. No ceiling was constructed. In essence, these represent the exact construction procedure of a building in the locality. See Fig. 2 for the AutoCAD drawings of the field model.

2.4. Construction of Green Roof

Boxes about 100mm deep were made with the same corrugated iron sheet used on the roofing of the structure and timber, such that, the top of the box was open. The corrugated sheet lying below was perforated in order to aid drainage of the green roof. A soil layer was later added about 90mm in depth to serve as the growing medium of the vegetation used. 6 boxes were made that covered the entire roof area. The boxes were the placed on the roof. A species of Mesembryanthemum plant, abundant in Kenya was used. The plant has a characteristic suitable for green roof usage i.e. low height, quickly spreads to cover planting area, succulent and evaporative cooling.

2.5. Instrumentation

Ref. [14] used HOBO instruments in their research in predicting the envelope performance of commercial office buildings in Singapore. The logger recognizes Smart Sensors plugged into the logger and collects data about various parameters. The connections between the Smart Sensors and the logger are digital, ensuring accurate, reliable data collection and storage. The logger, together with other sensors (for outdoor temperature/RH, solar radiation, wind speed and wind direction) were mounted on a tripod mast. The 3 metre mast (M-MPA) was bolted on a slab elevated 3 metres above the ground. This height places it in a good position to measure wind and solar radiation. All data logs into the logger from the 6 sensors (4 as mentioned above and 2 placed inside the two field models) and is downloaded via computer software called HOBOware, from Onset HOBO, the manufacturers of the sensors.

Solar radiation was measured using the Silicon Pyranometer smart sensor (S-LIB-M003), designed to work with the Onset HOBO Weather Station logger. Wind speed was measured using Wind Speed smart sensor (S-WSA-M003), designed to work with Onset HOBO station loggers. Wind direction of the wind speed measured above was also recorded using the Wind Direction smart sensor (S-WDA-M003), also designed to work with Onset HOBO station loggers. See Fig. 3 for the image of the Onset weather monitoring device installed.

Figure 3. *Image of the installed Onset weather monitoring device.*

Due to unavailability of only one type of instrument from a single manufacturer, two types of sensors from 2 different manufacturers that both measure temperature and humidity were used to carry out the measurement of the microclimate parameters at the field models. In total, there were 5 sensors recording both temperature and relative humidity at the same time. A single sensor deployed outside taking the outdoor temperature and relative humidity and 2 other, measuring the indoor temperature and relative humidity in both field models. All three mentioned above are from Onset HOBO manufacturer. The other 2 (from Tinytag) were placed just below the roofs inside the two models. Ref. [15] used it in their research in comparing the different thermal properties of building materials in Turkey. The measurement that was used for model validation and prediction were from HOBO. While the measurement from Tinytag instruments were only used in analyzing and discussing temperature differences below the green roof and the conventional (bare) roof.

3. Results and Discussions

Tables 1.0 and 2.0 show the summary statistics of the all the temperature readings plotted in the graphs for Test A and Test B respectively. Fig. 4 shows the graph of temperature recorded by the sensors placed just below the roofs for Test A, as shown in Fig. 2. A maximum and minimum reading of 32.57°C and 17.93°C was recorded in Bare Roofed Urban Building (BRUB) against 30.51°C and 17.53°C recorded in Green Roofed Urban Building (GRUB). The mean value recorded in the GRUB is 22.86°C while that of BRUB is 24.48°C. The measurements of the GRUB were averagely 1.6°C lower than those recorded in the BRUB. In the United States, 1°C increase in temperature would increase peak electricity demand by 2-4% when temperature exceeded 15-20° C [16]. Looking at Fig. 5, the maximum temperature difference between GRUB and

BRUB was recorded as 8.12°C. This huge difference in indoor temperature readings of GRUB and BRUB shows a large potential for reducing the amount of time air conditioners need to be on for cooling the inner environment. Less operating time to bring temperatures down to normal room temperature of 25°C means less energy consumption otherwise called cooling loads.

The investigation of the degree of temperature reduction offered by the green roof showed that an average of 2.16°C difference was maintained during the daytime (see Fig. 5). The peak difference recorded during the daytime was 6.494°C at 2.00pm on 1st June, 2014. During the nights of the observation period, there was an average difference of 3.92°C between the indoor temperature of the green roofed urban building and the outdoor temperature. The lowest difference between the two measurements is negative 7.387°C, recorded at around 1.20am on 2nd June, 2014.

This phenomenon shows that green roofs effectively provide thermal insulation during cold weather. Furthermore, this thermal insulation would mean the energy used in heating the indoor environment will be reduced due to heat entrapment. Considering there is no ventilation system, the indoor thermal environment fluctuated less, thus, more heat was conserved.

Table 1. *Temperature readings (°C) for Test A*

	GRUB	**BRUB**		**Outdoor measurement**			**GRUB**	**BRUB**		**Outdoor**		
	Temp just below roof		**B-G**	**O**	**O-G**	**O-B**	**Temp btw roof and floor**		**B-G**	**Outdoor**	**O-G**	**O-B**
Mean	22.86	24.48	1.62	20.33	-2.50	-3.98	22.50	23.13	0.63	20.33	-2.20	-2.80
Standard Error	0.03	0.04	0.03	0.08	0.06	0.03	0.04	0.04	0.01	0.08	0.06	0.06
Standard Deviation	1.97	3.02	2.05	3.79	3.04	1.41	1.77	1.93	0.45	3.79	3.10	2.82
Minimum	17.53	17.93	-5.76	12.00	-7.73	-7.56	17.65	18.03	-0.58	12.00	-7.39	-7.36
Maximum	30.51	32.57	8.12	30.52	5.94	0.57	26.57	27.65	1.67	30.52	6.49	5.00

Key: GRUB = G, BRUB = B, Outdoor = O.
O-G = Temperature/RH difference between outdoor and indoor readings in GRUB.
O-B = Temperature/RH difference between Outdoor and indoor readings in BRUB.
B-G = Temperature/RH difference between GRUB and BRUB values.

For Test B, a maximum reading of 28.99 °C was recorded just below the bare roof against 25.82°C recorded in GRUB. Averagely, the indoor temperature in GRUB is 20.91°C and 21.26°C in BRUB. From this, it is quite clear that temperature readings for Test B are all lower than the Test A scenario. A z-test was used to analyze the temperature differences (column 3: B-G, in both tables) recorded between GRUB and BRUB for both Test A and Test B. The results showed that there was a significant difference between the temperature differences of the different treatments. Hence, the difference could be attributed to the closeness of an office block that is just 4m away from GRUB when considering Test B. BRUB for Test B is standing far away from any building, thus favouring airflow in all directions, whereas the office block could have obstructed air flow from the west direction of GRUB.

When the outdoor temperature recorded was compared with the previous readings measured inside the buildings for Test A (see Fig. 5), a negative difference was recorded i.e. the temperatures inside the buildings were averagely higher than the temperature outside. This is because of the cold season that crept in during the field study. As a result, green roofs will be useful in cold areas or during cold season.

This is a climate variability. However, during the hottest days, when the outdoor temperature was higher than the indoor temperatures, the maximum temperature difference recorded was 5.94°C and 0.57°C for GRUB and BRUB respectively.

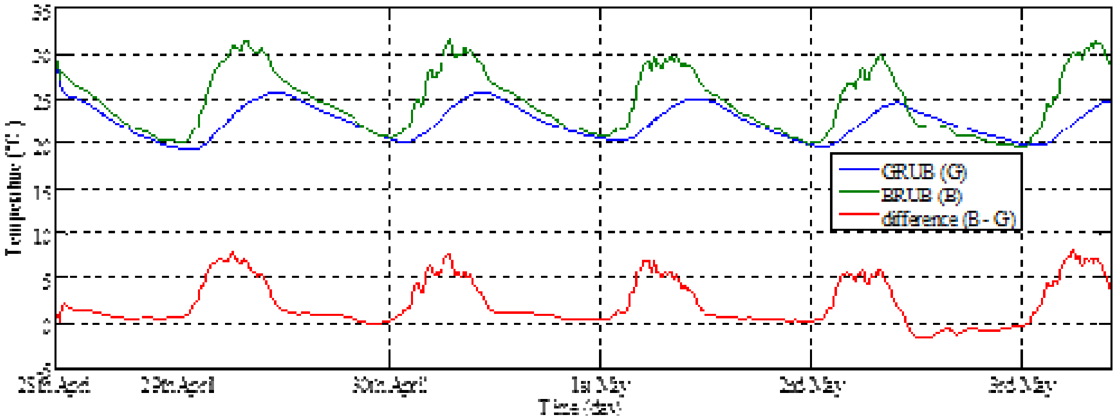

Figure 4. *Temperature readings just below the green roof*

Table 2. *Temperature readings (°C) for Test B*

	GRUB	BRUB		Outdoor measurement			GRUB	BRUB		Outdoor		
	Sensor below roof		**B-G**	**O**	**O-G**	**O-B**	**Temp btw roof and floor**		**B-G**	**Outdoor**	**O-G**	**O-B**
Mean	20.91	21.26	0.36	18.41	-2.50	-2.85	20.80	20.51	-0.30	18.41	-2.39	-2.10
Standard Error	0.03	0.03	0.02	0.05	0.04	0.02	0.02	0.02	0.01	0.05	0.04	0.03
Standard Deviation	1.71	2.34	1.42	3.26	2.64	1.44	1.62	1.67	0.44	3.26	2.72	2.33
Minimum	16.49	15.46	-2.42	8.42	-8.90	-8.81	16.51	15.63	-1.72	8.42	-8.49	-7.37
Maximum	25.82	28.99	5.56	27.85	4.28	1.24	25.60	25.62	0.94	27.85	4.79	4.32

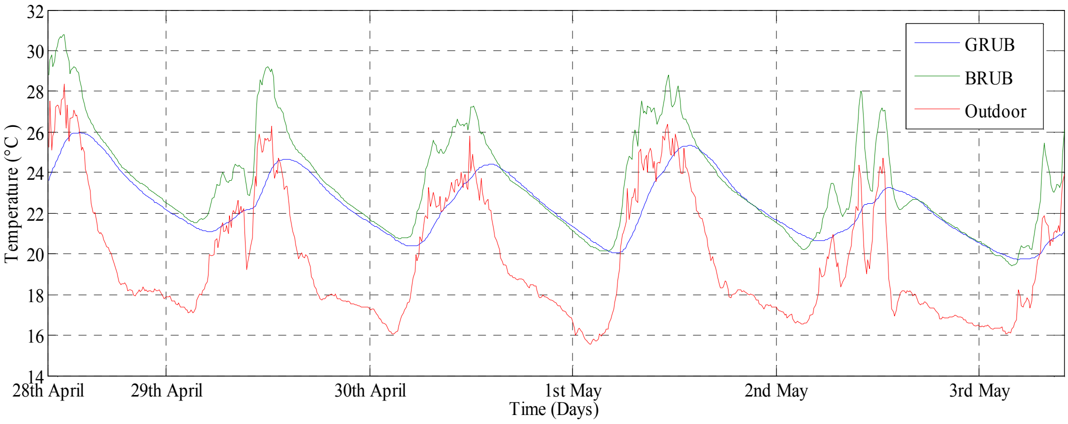

Figure 5. *Comparison of outdoor and indoor temperature readings*

This was the maximum effect the green roofs have showed in heat gain reduction for this study. Thus, less indoor temperature will be recorded if buildings are covered with living vegetation. This is also the same case for Test B but only of lesser magnitude in terms of temperature reduction. The reason for the lower magnitude can be attributed to close proximity of GRUB to an office building as earlier mentioned.

Fig. 6 shows the temperature measured for Test A with the sensor placed just midway position (equidistant from the roof and floor) in the buildings. See Fig. 2 for the positions of the sensors. An average of 22.5°C and 23.13°C was measured in GRUB and BRUB respectively. Both averages had a standard error of 0.04. There was a maximum temperature difference of 1.67°C between GRUB and BRUB that was recorded. The average mean temperature difference between BRUB and GRUB was 0.63°C. Compared to the previous average of 1.6°C recorded for temperature readings just below the roofs, this shows a drop in the magnitude. This was due to the invariable nature of heat seeking lower potential always. Despite the fact that the degree in mean temperature differences between the two houses reduced by 0.97, the effect of the green roof in temperature reduction was obvious. This was also the case for Test B. All findings showed similarity to the Test A case. And this was affirmed by a z-test that was carried out to investigate whether there is a significant difference between the means of differences of temperature measurement of Test A and B. The result showed that there was a significant difference between the two measurements.

Fig. 7 shows the comparison of outdoor temperature measurements with temperature measurements at a halfway between the roof and floor of the in the buildings for Test A. Like with the case of temperature readings just below the roofs, outdoor temperatures here are averagely lower than those measured in the buildings. Same reason of cold season applies here. An average of -2.20 and -2.80°C between outdoor measurement and the measurements in the GRUB and BRUB were recorded respectively. The differences between outdoor and indoor temperature readings of GRUB and BRUB were compared and the results showed a minimum of -8.42°C and -7.37°C and a maximum of 4.79°C and 4.32°C respectively. For the minimum value, that occurred when it was very cold outside shows that GRUB retain more heat gained during the daytime than BRUB. Therefore, the average heating time building users will use their room heaters in order to raise the temperature to a more conducive one is reduced, hence, reducing heating load.

4. Relative Humidity

Measurements of relative humidity were also carried out at the same points as for the temperature. Table 3.0 and 4.0 shows the summary of all statistical analysis of all readings of relative humidity for Test A and Test B. Fig. 8 shows the values of relative humidity measured just below the roofs and the differences between BRUB and GRUB values. The mean relative humidity of GRUB was 91.16% against 75.14% in BRUB. Averagely, the values recorded in GRUB were higher than that recorded in BRUB.

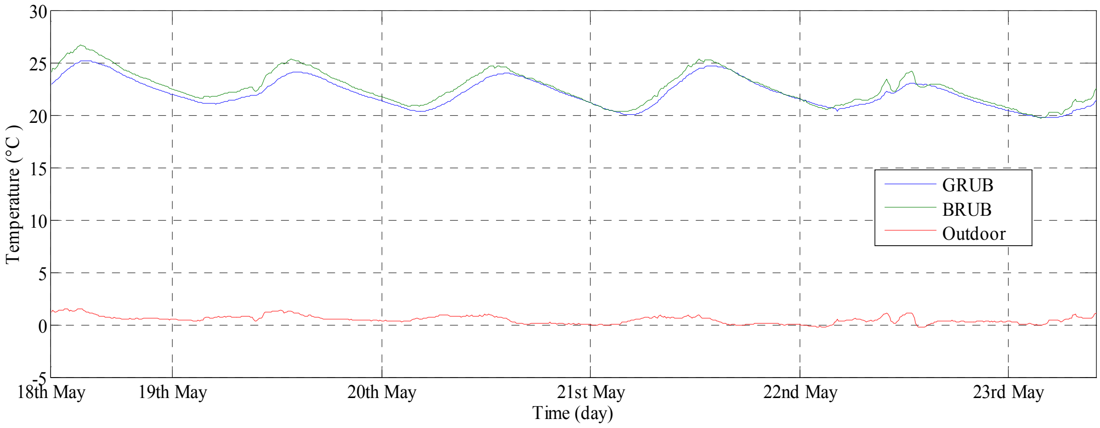

Figure 6. *Temperature readings measured equidistant between the roof and floor in the two buildings*

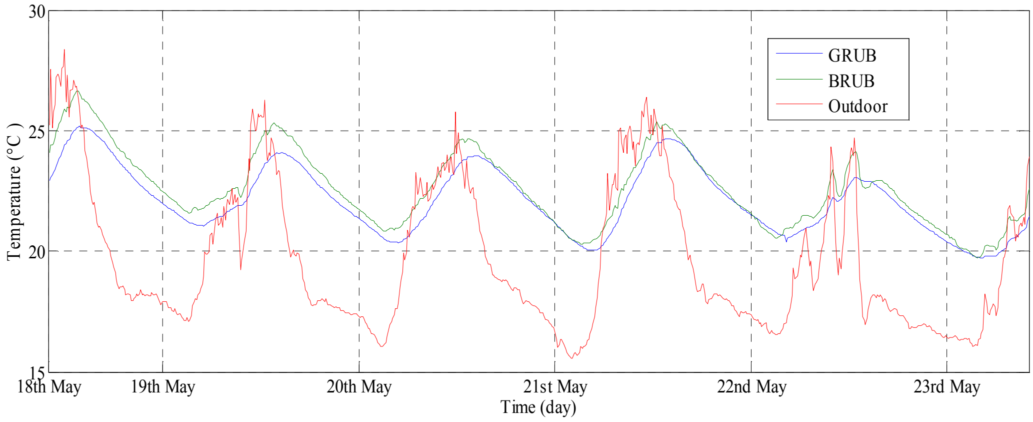

Figure 7. *Comparison of outdoor temperature with indoor temperature midway in the models*

An average difference of -16.02% was recorded. The GRUB shows a higher retention capacity for indoor moisture. This is due to the added layer of green roof that not only prevents moisture from getting in, but also from going out. On the 3rd of May, 2014, when the ambient weather was extremely cold, RH readings in both buildings peaked at 100%. This shows moisture escapes faster with the conventional roof when compared with the green roof. Surprisingly, for Test B, the RH didn't tally with the trend of measurements in Test A. BRUB logged higher RH values. An average of 83.63% against GRUB's average of 76.3% was recorded. This awkward result may be possibly due to the high fluctuation rate of the BRUB. Because of less insulation, more RH accrues faster than in GRUB. And considering the measurements obtained in the cold season were long.

The outdoor relative humidity measured was compared with the indoor relative humidity measured just below the roofs in both GRUB and BRUB. See Fig. 9. Outdoor measurements were averagely lower than indoor measurements. When the outdoor measurement was compared with that in GRUB, an average difference of 14.54% was recorded. However, for the BRUB, a small average difference of 0.69% was recorded. The maximum difference between the outdoor RH and GRUB indoor RH is higher than the corresponding value of BRUB.

Table 3. *Relative humidity readings (%) for Test A*

	GRUB	**BRUB**		**Outdoor measurement**			**GRUB**	**BRUB**		**Outdoor**		
	RH just below roof		**B-G**	**Outdoor**	**O-G**	**O-B**	**RH btw roof and floor**		**B-G**	**Outdoor**	**O-G**	**O-B**
Mean	91.16	75.14	-16.02	71.50	-14.54	0.69	84.37	74.80	-9.57	71.51	-12.52	-3.01
Standard Error	0.11	0.13	0.09	0.37	0.31	0.24	0.08	0.11	0.04	0.37	0.33	0.32
Standard Deviation	7.77	9.77	6.94	18.01	15.04	11.73	4.03	5.28	2.01	18.01	16.91	16.07
Minimum	48.81	44.22	-55.79	27.10	-51.08	-28.55	70.30	58.10	-17.30	27.10	-54.20	-43.50
Maximum	100.00	100.00	24.61	98.30	11.58	20.84	92.10	86.00	-5.20	98.30	13.30	20.60

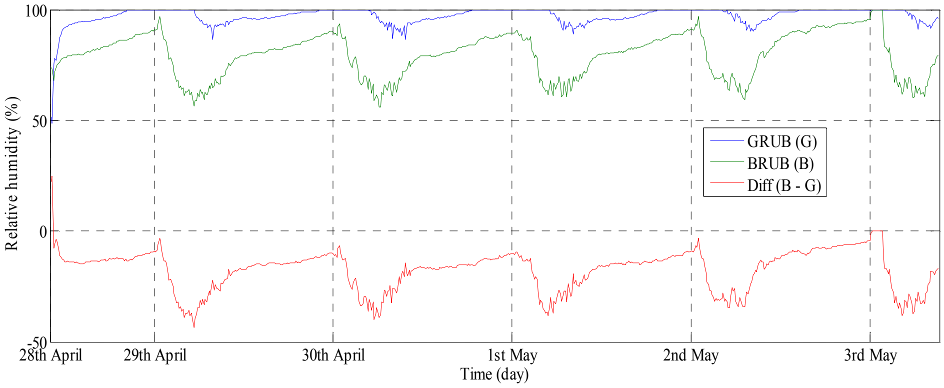

Figure 8. *Graph of RH measured just below the roofs*

Fig. 10 shows values of RH measured midway in both models and their differences. An average of 84.37% was recorded in GRUB against a lower value of 74.8% in BRUB. Both of these averages, when compared with those measured just below the roofs were lower. However, the average minimum values measured midway in the two models are higher than the corresponding values just below the roof. This suggests that the proximity to the roof has a higher potential for changes. Due to the windows being shut, which are mostly at the midway positions of houses, there was no support for quicker fluctuations. Conversely, for Test B, the RH in BRUB are higher than in GRUB. This behaviour suggests the role air flow outside the building plays in cooling off buildings. The GRUB which experiences lower wind effect on its envelope possesses lower RH compared with the values of Test A.

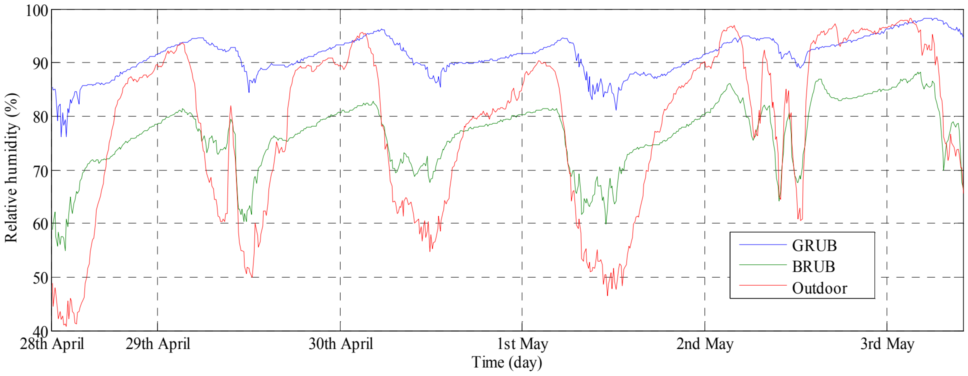

Figure 9. *Comparison of outdoor and indoor RH measured just below the roof*

Table 4. *Relative humidity readings (%) for Test B*

	GRUB	**BRUB**		**Outdoor measurement**			**GRUB**	**BRUB**		**Outdoor**		
	RH below roof		**B-G**	**Outdoor**	**O-G**	**O-B**	**RH btw roof and floor**		**B-G**	**Outdoor**	**O-G**	**O-B**
Mean	76.30	83.63	7.33	77.62	0.93	-5.89	76.69	83.51	6.82	77.62	0.93	-5.89
Standard Error	0.08	0.10	0.06	0.21	0.20	0.20	0.07	0.05	0.03	0.21	0.20	0.20
Standard Deviation	5.39	7.09	4.38	14.58	13.74	13.32	4.64	12.94	3.00	14.58	13.74	13.32
Minimum	61.35	59.56	-8.38	39.30	-35.20	-42.20	65.80	70.30	-0.20	39.30	-35.20	-42.20
Maximum	87.65	100.00	19.06	99.70	27.80	17.40	86.10	91.50	12.30	99.70	27.80	17.40

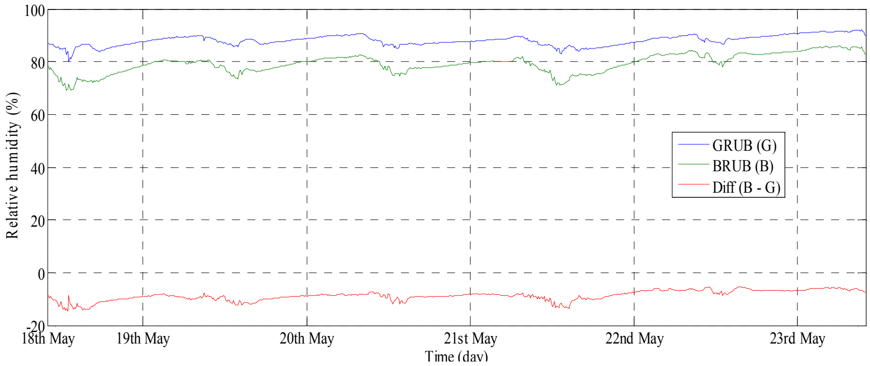

Figure 10. *Graph of RH measured in GRUB and BRUB*

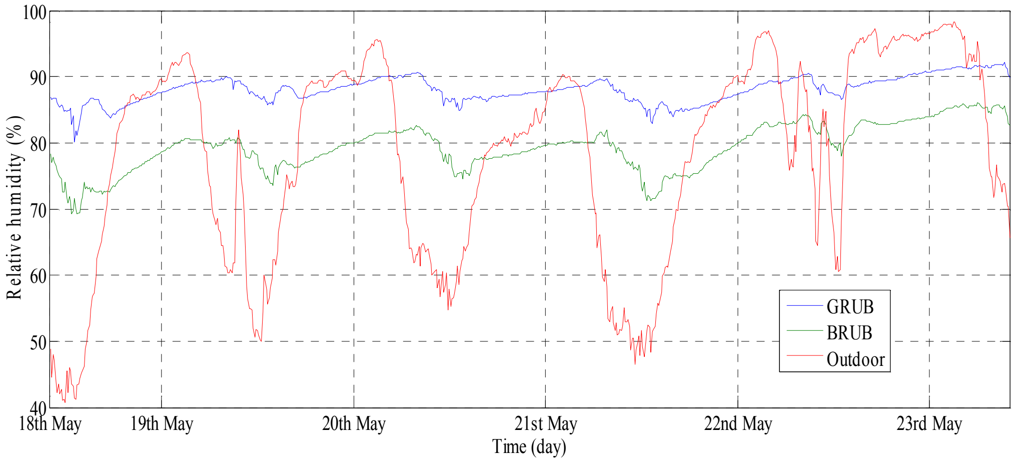

Figure 11. *Comparison of RH of GRUB, BRUB and with outdoor measurement.*

Fig. 11 shows the comparison of outdoor RH and indoor RH measured midway in the 2 models. Outdoor measurement was averagely lower than all the indoor readings. At maximum outdoor RH (98.3%), maximum indoor RH was 92.10% in GRUB and 86.0% in BRUB. At a minimum outdoor RH of 27.10%, indoor measurements were 70.3% in GRUB and 58.1% in BRUB, suggesting more moisture entrapment capacity by GRUB. However this wasn't the trend for Test B. RH values were lower in GRUB as compared to BRUB. This suggests that the higher exposure capacity of BRUB to the environment as opposed to the obstructed office block near the GRUB, enhanced moisture gain and loss in it.

5. Conclusion and Recommendation

The differences of indoor microclimate of Green Roofed Urban Building (GRUB) and Bare Roofed Urban Building (BRUB) built in a sub-Saharan climate were evaluated in this study. The field models built were monitored under a no-ventilation condition. Indoor microclimate; air temperature and relative humidity parameters, of GRUB and BRUB were compared. An average of 22.5°C and 23.13°C was measured in GRUB and BRUB respectively. Both averages had a standard error of 0.04. There was a maximum temperature difference of 1.67°C between GRUB and BRUB. The average mean temperature difference between BRUB and GRUB was 0.63°C. The lower temperature value existing in GRUB signifies the effect of the green roof in heat insulation which subsequently reduces the cooling load requirement in GRUB.

When differences in temperature readings between Outdoor and indoor temperature of GRUB and BRUB were compared, the results were a minimum of -8.42°C and -7.37°C and a maximum of 4.79°C and 4.32°C respectively. For the minimum value, that occurred when it was very cold outside shows that GRUB retain more heat gained during the daytime than BRUB. An average of 84.37% relative humidity was recorded in GRUB against a lower value of 74.8% in BRUB. Outdoor measurement was averagely lower than all the indoor readings. At maximum outdoor RH (98.3%), maximum indoor RH was 92.10% in GRUB and 86.0% in BRUB. At a minimum outdoor RH of 27.10%, indoor measurements were 70.3% in GRUB and 58.1% in BRUB, a significant difference between the two that suggests more moisture entrapment capacity by GRUB.

Further research work could consider carrying out the field evaluation when city temperatures are at highest. Also, the percentage changes of the indoor microclimate could be determined by varying the percentage of roof area covered by the green roof. From the foregoing statement, this research considered a 100% roof coverage.

When this study started, average temperature within the region was relatively high above 20°C. However, as the measurement period extended into July, cold season crept in, and the average temperature became a lot lower than the previous temperatures, around 18°C. This led to shorter measurement period of the effect of green roofs on heat gain reductions in buildings. Future research could consider carrying out his research between the months of January and March, or when the temperature of the area is hottest for a longer period of time.

Secondly, this research could either be conducted in two other scenarios. One is a denser environment with observation models close to other buildings, in order to replicate real life scenarios of urban built environment. And two, is to build the models far away from any obstruction, in order to ascertain the effect of green roofs alone on the heat gain reduction.

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