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THERMAL COMFORT PERCEPTION OF OCCUPANTS IN AN UPCYCLED BOTTLE HOUSE IN ABUJA, NIGERIA

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Abstract

Several studies have shown that the use of upcycled materials for construction is a viable intervention for delivering affordable and adequate housing in low-income communities. However, information regarding in-situ performance of buildings made from upcycled materials is scarce in the literature. This paper compares the thermal performance of a building with walls made of sand-filled plastic bottles (Bottle House) with two other conventional buildings, one made of mud bricks (Mud House) and another made of sandcrete blocks (Cement House). In order to obtain the thermal sensation vote (TSV) of the occupants, thermal comfort questionnaires were developed based on ISO 7730 standard using the seven-point ASHRAE thermal sensation scale. Also, a Testo 480 multifunction meter which comprised of an anemometer, radiant globe thermometer, air thermometer, and Relative Humidity probe, was used to concurrently calculate the predicted mean vote (PMV). From the results of the thermal sensation votes (TSV) based on occupant's survey, mean vote from participants of -2.0, 2.0 and 2.5 were observed for the bottle house, mud house and cement house respectively. In comparison, using the extended PMV thermal comfort model better suited for non-air-conditioned buildings in warm climates, adjusted PMV mean values of 1.9, 2.1 and 2.1 were recorded for the bottle house, mud house and cement house respectively. The TSV and PMV results both indicate that occupants of the bottle house felt more thermally comfortable when compared to occupants in the other dwellings. The results of this paper will provide evidence on the prospects of upcycling plastic waste for construction and its impact on occupant's thermal comfort when compared to conventional building materials.

1. INTRODUCTION

The climates in sub-Saharan Africa are largely tropical, with many cities reporting high average ambient temperatures, this consequently leads to extreme indoor thermal environments, which have been linked to negative impacts on health, wellbeing and productivity. This overheating challenge is more severe in low-income urban and peri-urban communities which are usually densely populated and poorly ventilated, due to the housing crises [1]. This challenge is expected to worsen, since the UN has predicted Africa to be the most vulnerable to the impacts of climate change.

Research on using upcycled materials for building low-cost houses has been considered a viable solution to address inadequate housing in low-income communities[2]. Several scholars have reported using upcycled materials such as plastic waste [3–6], agricultural waste[7–9] and fibre waste[10–12]. The comprehensive review presented by [13] shows that numerous studies have investigated the thermal performance of upcycled materials for constructing homes, however these have mainly been at the component level. A few studies [14,15] have predicted the performance of buildings from upcycled materials using simulation study, however, data on experimental in-situ measurements and/or qualitative studies are scarce. This paper contributes to filling this gap by reporting on thermal performance of a low-cost building made from upcycled plastic waste. It complements the few studies which have reported on thermal comfort in low-income dwellings in the developing world, such as [16] who studied thermal comfort in low- and middle-income dwellings in Abuja, Nigeria and [17] who did a similar study in Uganda. Furthermore, this study makes a unique contribution as it compares the performance of the bottle house (which has an unconventional material as the envelope) with conventional buildings (mud and cement) [26].

This study is part of the Bottle House project, which is an international, transdisciplinary, collaboration between academia, industry and end-users in a low-income community of Nigeria [2,6,18–20]. The project explored the design and building of an affordable, sustainable home from upcycled materials; the walls were constructed using plastic bottles, ceiling from used bamboo scaffolding and the floor was created from recycled tiles. The Bottle House, shown in Figure 1, is situated in Abuja, the Federal Capital Territory of Nigeria.

Figure 1. Bottle house in Paipe, Abuja, Nigeria [2].

As this is a new building made using upcycled plastic bottles, no data is available on the post-occupancy thermal sensation of occupants in the Bottle house. This study seeks to encourage the adoption of the Bottle House for affordable housing by conducting a thermal comfort survey of these occupants as thermal comfort is an important parameter to consider for any building especially regarding building energy performance. This paper also compares the results obtained to typical building typologies found in the study area. Post occupancy evaluations to monitor indoor environmental conditions and assess occupants' thermal comfort using surveys have similarly been done by [16,21,22] using Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) thermal comfort models. BS EN ISO 7730:2005 [23] describes the Predicted Mean vote (PMV) as an index that predicts the mean value of the votes of a large group of persons exposed to the same environment on the 7-point thermal sensation scale (Table 1), based on the heat balance of the human body. The PMV thermal comfort model has been used extensively over the years in various studies and various climates.

Table 1. Correlation between two ASHRAE short-term thermal comfort scale (TSV) and PMV [22,24].

	TSV	PMV
	Hot	+3
Short-term	Warm	+2
Thermal	Slightly warm	+1
Comfort	Neutral	0
Acceptable	Slightly cool	-1
Range	Cool	-2
	Cold	-3

According to Fanger and Toftum (2002) [43], the PMV model predicts occupants' thermal sensation based on level of activity and clothing, and environmental factors such as air temperature, mean radiant temperature, air velocity and humidity. It has the advantage of including major factors affecting occupants' thermal sensation regardless of HVAC system, indoor thermal environment, activity or clothing level. However,[22] explains that PMV overestimates thermal sensations in warm climates without considering human acclimatisation. PMV also has delimitation of not being able to evaluate occupants' perception and hence the need for Thermal Sensation Vote (TSV) as utilized in this study. Likewise, PMV scale is the only scale correlated to TSV which can convert the verbal ranges to numerical values. According to [22], TSV allows for the evaluation of occupants' thermal sensation and is based on the individual's thermal perception. Another major reason for the discrepancy between TSV and PMV is that it is difficult to measure accurate values for metabolic rates and clothing insulation[25].

2. MATERIAL AND METHODS

2.1 CASE STUDY DESCRIPTION

Abuja is situated in central Nigeria at latitude 9° 07 ʹN and longitude 7° 48ʹ E, at an elevation of 840 m (2760 ft) above the sea-level and is located within the Savannah zone vegetation of the West African sub region with patches of rain forest [26,27]. Temperatures ranges from 12 °C to 40 °C during the dry Harmattan (dry and dusty) season (November – March) [16,26,27]. Precipitation ranges from 305 to 762 mm (12–30 in.) in the rainy season (April - October) [16,26,27]. Abuja's distinctive geographical features such as the high altitudes and undulating terrain act as a moderating influence on the weather of the city. In total five buildings were used for the data collection. Two houses built with cement blocks, two houses built with hand-formed mud and the Bottle house (Figure 2).

Figure 2. Buildings used for data collection (a) Cement (b) Mud (c) Bottle house.

These were all selected from the same area in Paipe, Abuja. The external wall U-values for the Bottle House, Mud Houses and Cement houses were 2.94, 2.62 and 4.0 W/m^2 [20]. It is noteworthy to mention that all the houses were naturally ventilated with some houses having mechanical fans to improve indoor comfort, although these were not in operation during the measurement period.

2.2 ENVIRONMENTAL MONITORING AND THERMAL COMFORT SURVEY

The calculated PMV estimates the mean response of occupants to their thermal environment and was determined using the six parameters; air temperature, mean radiant temperature (MRT), relative humidity (RH), air velocity, clothing insulation level (clo) and metabolic rate (met). The TSV on the other hand is the actual thermal sensation vote of the occupants and is obtained from the questionnaire results by asking the occupants to vote how they felt in relation to the ASHRAE 7-point thermal sensation scale [24].

During the field investigation each participant took part in a single experimental session in their living rooms. All of the dwellings used the same experimental layout. During each session, measurements were taken both subjectively (using the ASHRAE 7-point thermal comfort questionnaire [24]) and objectively (using a Testo 480 multifunction metre [28] that included an anemometer, radiant globe thermometer, air thermometer, and RH). To control the metabolic rate, participants were invited to sit down in their living room and either undertake sedentary work or rest during the sessions.[28] Manufacturer's specifications of the Testo 480 multifunction meter [28] is presented in Table 2 below.

Table 2. Instruments for physical measurements.

Name	Parameters	Measurement range	Accuracy
Testo 480 multifunction meter	Air temperature	0 to +50 °C	± 0.5 °C
	Mean radiant temperature	0 to +120 °C	Class 1
	Relative humidity	0 to 100 % RH	± (1.8 %RH + 0.7% of m.v.)
	Air velocity	0 to +5 m/s	± (0.03 m/s +4% of m.v.)

Thermal comfort questionnaires were developed based on BS EN ISO 7730 standard [2005][23] using the seven-point ASHRAE thermal sensation scale . These were administered to the occupants of the cement house, mud house and the bottle house (Figure 3) with 3-4 adult respondents from each house.

Figure 3. Data collection from occupants (a) Cement (b) Mud (c) Bottle house.

This data was used to estimate the thermal sensation vote (TSV) and compare to the Predicted Mean Vote (PMV) calculated for the occupants. Participants were asked to complete the questionnaires throughout the physical measurement period. Data for both comfort survey and monitored readings were collected in April, which is the end of dry season and the beginning of rainy season in Nigeria. It is also one of the months with the hottest temperatures throughout the year. Average outdoor temperature in April is 28.6^{o}C with maximum of 33.8^{o}C and minimum of 24^{o}C [29] while the relative humidity is 57% [41].

3. RESULTS AND DISCUSSION

3.1 THERMAL SENSATION VOTE (TSV)

The TSV values were calculated based on the values recorded in the questionnaires. The responses to the questionnaire, which were used to calculate the TSV are presented in Table 3.

Table 3. TSENS votes of building occupants.

Participant	**Q1: Your activity level now**	**Q2: How are you feeling at this precise moment?**	**Q3: Do you find this . . .?**	**Q4: Please state how you would prefer to be now?**	**Q5: How do you judge this environment (local climate) on a personal level?**	**Q6: Please state your personal tolerance of this environment. Is it . . .**	**Q7: Time of completing the survey**	
P1	2	-2	2	-3	1	0	12:10	BH
P2	2	-2	0	0	1	0	12:12	
P3	2	-2	0	0	1	0	12:12	
P1	1	0	1	-3	3	2	12:30	MH 1
P2	2	1	0	-2	1	0	12:30	
P3	2	3	3	-3	4	3	12:30	
P1	2	2	2	-3	3	1	13:00	MH 2
P2	2	2	2	-2	3	1	13:00	
P3	2	3	3	-3	3	3	13:00	
P4	3	1	1	-2	1	1	13:00	
P1	2	2	0	0	1	0	11:42	CH 1
P2	2	3	1	-3	3	0	11:42	
P3	2	2	0	-1	1	0	11:42	
P4	2	2	0	-1	1	0	11:42	
P1	2	2	0	-2	2	3	12:00	CH 2
P2	2	3	0	-2	3	0	12:00	

These responses were obtained from all participants in the afternoon. As this was done inside their homes, the clothing worn by the participants was casual and also lightweight typical of hot climate regions. The women were dressed in a light blouse/t-shirt and a skirt/ native wrapper while the men typically wore t-shirt and trousers or native kaftan typical of the local region. The average clothing insulation (clo) was 0.30 and the metabolic rate (met) was 1.0 (seated, relaxed) as indicated by majority of the participants. These values were calculated using the BS EN ISO 7730 standard [23]. This shows that their clothing and level of activity did not exaggerate their thermal perception [22,23]. All participants from the Bottle house indicated TSV of -2 (cool) while responses from participants in other house types ranged from 0-3 (neutral to hot) with those in the cement houses (CH 1 and 2) indicating only +2 and +3 (warm; hot). When asked how they would prefer to feel, most of the participants in the Bottle House (BH) indicated that they did not want any change while one occupant mentioned they would like to feel much cooler. In contrast majority of remaining 13 participants indicated that they would rather be cooler or much cooler. This disparity is also observed in the TSENS votes for Q5 and Q6.

3.2 PREDICTED MEAN VOTES (PMV)

Fanger's theory [30] was used to calculate the PMV values using the measured parameters. The Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) values were calculated by the testing equipment (Testo 480 multifunction meter). The operative temperature for each dwelling was also calculated as the average of the air temperature and the mean radiant temperature according to ASHRAE Standard 55 [24]. From Table 4, it can be observed that the average air temperature for the Bottle house over the measurement period was 32.2°C and mean radiant temperature was 32.7°C with operative temperature of 32.45°C.

Table 4. Measured temperature and PMV values

HOUSE TYPE	Values	MRT (°C)	Air temp (°C)	Calc. Operative temp (°C)	RH (%rH)	Air velocity (m/s)	PMV Calc	PPD Calc (%)
Bottle House	Mean	32.7	32.2	32.5	54.0	0.02	2.7	96.2
	Min	32.1	31.9	32.0	51.0	0.01	2.6	94.7
	Max	34.9	32.6	33.8	56.1	0.05	3.0	99.1
Mud House 1	Mean	35.0	34.7	34.9	51.1	0.05	3.0	99.1
	Min	35.0	34.6	34.8	49.9	0.03	3.0	99.1
	Max	35.0	34.8	34.9	51.7	0.06	3.0	99.1
Mud House 2	Mean	39.0	36.8	37.9	47.5	0.02	3.0	99.1
	Min	36.6	36.0	36.3	42.2	0.02	3.0	99.1
	Max	43.4	38.2	40.8	55.0	0.04	3.0	99.1
Cement House 1	Mean	33.7	33.2	33.45	60.4	0.02	3.0	99.1
	Min	33.5	32.8	33.15	59.5	0.01	3.0	99.1
	Max	34.4	33.5	33.95	61.0	0.03	3.0	99.1
Cement House 2	Mean	35.3	34.4	34.9	58.0	0.06	3.0	99.1
	Min	34.6	34.3	34.5	55.8	0.03	3.0	99.1
	Max	36.6	34.6	35.6	58.8	0.08	3.0	99.1

These values are much lower than that recorded in the other dwellings. This could be attributed to the overall components of the building envelope in the Bottle house having higher thermal resistance compared to that of the other dwellings[20]. This is also evident in the different PMV recorded, with the Bottle house also recording lower Percentage of persons dissatisfied (PPD) than the other dwellings. The PPD is calculated based on the number of thermally dissatisfied people in a group using the predicted mean vote (PMV). Acceptable thermal sensations, according to the PMV model should typically fall within -1 and +1 on the scale [31] therefore, these values indicate that the occupants are uncomfortable as they fall between +2 and +3 on the PMV scale. However, the PMV model has been tested over the years and has been noted to better predict thermal sensations in air-conditioned buildings when compared with non-air-conditioned buildings as it tends to overestimate the feeling of warmth [32]. This is supported by the fact that the thermal sensation (TSV) from the occupants in both the mud house and the bottle house are different from the PMV results recorded in Table 4.

All three occupants of the bottle house voted -2 on the TSV scale (Table 3) indicating that they felt cool within the dwelling which according to two out of the three participants was comfortable while for one participant this was uncomfortable. However, the PMV calculated for these occupants ranged between +2.6-3.0 (Very Warm-Hot). Similarly, in the other dwellings, the PMV calculated was +3 for all occupants indicating that the indoor environment is hot and uncomfortable. The TSV results, in contrast, show that the occupants voted between 0 and +3 which signifies that they felt slightly warm to hot, except one person who felt neutral. Only 4 out of 16 participant's true thermal sensation was accurately predicted by the PMV model. The difference is particularly glaring when comparing the thermal sensation votes for the occupants in the Bottle house to the calculated PMV.

This result can be compared to previous research in similar climates which show that the PMV comfort model overestimates the thermal comfort sensation of building occupants [33–35]. Hamzah et al. (2018) [34] carried out a survey of eight secondary schools in Indonesia using questionnaires to collect data in order to determine the thermal comfort of the students based on TSV. Although they recorded high air and radiant temperatures ranging from 28.2-33.6ºC, 80% of the students surveyed reported that they were comfortable. The errors resulting from this over-estimation of PMV, however, can be combated by using the extended PMV model for "non-air-conditioned buildings in warm climates" developed by Fanger and Toftum (2002) [32] which considers the different expectations of building occupants. This is calculated by using an expectancy factor, *e*, for the region under study, in this case Abuja, Nigeria. The expectancy factor is used to multiply the recorded PMV and give a better estimate of the thermal sensation of the building occupants in naturally ventilated buildings. According to Fanger and Toftum (2002) [32], for regions with year-round warm weather having no or few air-conditioned buildings, an expectancy factor of 0.5 or 0.7 respectively should be used. This study used the expectancy factor of 0.7 to get the adjusted PMV in Table 5.

Table 5. Comparison of observed Thermal sensation votes (TSV) with new PMV model.

	Expectancy factor, e	**Mean PMV recorded**	**PMV adjusted to occupants' expectation**	**Mean Thermal Sensation votes**
BH	0.7	2.7	1.9	-2.0
MH 1	0.7	3.0	2.1	2.0
MH 2	0.7	3.0	2.1	2.0
CH 1	0.7	3.0	2.1	2.3
CH 2	0.7	3.0	2.1	2.5

Using the extended PMV model brings the PMV values much closer to the TSV values as is evident in Table 5 above. On the PMV scale, +2.1 is considered 'Warm' which is a more accurate thermal sensation than 'Hot' (+3) which was initially recorded for the other dwellings. Furthermore, Fang et al. (2017) [36]observed in their study that with operative temperatures higher than 34ºC, PMV is less accurate and discrepancy between PMV and TSV arises with increasing operative temperature. It is noteworthy to mention that although the PMV adjusted to occupants' expectation for the other dwellings are similar to the mean thermal sensation votes, that for the bottle house is different and is still significantly less than that recorded for the other dwellings. The slightly better performance could be attributed to the deliberate design features incorporated to improve thermal performance as detailed in [2]. These include, water filled bottles to increase thermal mass, orientation of the building to improve natural ventilation and light-coloured painted walls to reduce radiant temperature.

4. CONCLUSIONS

This study has considered the use of waste plastic bottles for housing construction for low-income householders in Nigeria which is novel when compared to existing research. The study went further to conduct post-occupancy surveys for the bottle house to determine thermal sensation votes (TSV) of the occupants and comparing this with the Predicted mean vote (PMV) calculated using experimental readings. These figures were also compared to two popular building typologies (mud and cement) which are typically found in this location. The results of this paper show that occupants of the bottle house felt thermally comfortable even though measured indoor conditions suggest otherwise. In any case, the bottle house had the best performance compared to the other houses. This was attributed to the intentional measures incorporated during the bottle house construction.

Although this paper provides novel insights on in-situ thermal performance of the bottle house, it has some limitations. One such limitation is the sample size as only 16 respondents in total, therefore, further study needs to use a larger sample size, with a longer term thermal comfort survey and environmental monitoring over different times / periods of the year not just during the hottest month. The TSV records short-term thermal perception of occupants, as such longer periods of observation and measurement will immensely improve the findings of this study.

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References

[1] Olotuah, A.O.; Bobadoye, S.A., 2009. "Sustainable housing provision for the urban poor: a review of public sector intervention in Nigeria", The Built and Human Environment Review 2, 51–63.

[2] Oyinlola, M.; Whitehead, T.; Abuzeinab, A.; Adefila, A.; Akinola, Y.; Anafi, F.; Farukh, F.; Jegede, O.; Kandan, K.; Kim, B.; Mosugu, E., 2018. "Bottle house: A case study of transdisciplinary research for tackling global challenges", Habitat International 79, 18–29.

[3] Mansour, A.M.H.; Ali, S.A., 2015. "Reusing waste plastic bottles as an alternative sustainable building material. Energy for Sustainable Development", 2015, 24, 79–85.

[4] Mokhtar, M.; Sahat, S.; Hamid, B.; Kaamin, M.; Kesot, M.J.; Wen, L.C.; Xin, L.Y.; Ling, N.P; Lei, V.S.J., 2015. “Application of plastic bottle as a wall structure for green house”, ARPN Journal of Engineering and Applied Sciences 11, 7617–7621.

[5] Muyen, Z.; Barna, T.N.; Hoque, M.N., 2016. “Strength properties of plastic bottle bricks and their suitability as construction materials in Bangladesh”, Progressive Agriculture 27, 362–368.

[6] Kim, B.; Wisniewski, J.; Baker, T.; Oyinlola, M., 2019. “Behaviour of sand-filled plastic bottled clay panels for sustainable homes”, Journal of Building Engineering 26, 100895.

[7] Ghavami, K., 1995. “Ultimate load behaviour of bamboo-reinforced lightweight concrete beams”, Cement and Concrete Composite 17, 281–288.

[8] Sales, A.; Lima, S.A., 2010. “Use of Brazilian sugarcane bagasse ash in concrete as sand replacement”, Waste Management 30, 1114–1122.

[9] Korjenic, A.; Petránek, V.; Zach, J.; Hroudová, J., 2011. “Development and performance evaluation of natural thermal-insulation materials composed of renewable resources”, Energy & Buildings 43, 2518–2523.

[10] Mohammadhosseini, H.; Alyousef, R., 2021. “Towards Sustainable Concrete Composites through Waste Valorisation of Plastic Food Trays as Low-Cost Fibrous Materials”, Sustainability, 2021, 13, 2073.

[11] Kammoun, Z.; Trabelsi, A., 2019. “Development of lightweight concrete using prickly pear fibres”, Construction and Building Materials 210, 269–277.

[12] Islam, M.S.; Ahmed, S.J., 2018. “Influence of jute fiber on concrete properties”, Construction and Building Materials, 2018, 189, 768–776.

[13] Messahel, B.; Onyenokporo, N.; Takyie, E.; Beizaee, A.; Oyinlola, M., 2023. “Upcycling agricultural and plastic waste for sustainable construction: a review”, Environmental Technology Reviews, 2023, 12, 37–59.

[14] Tarabieh, K.A.; Nassar, K.; Sharkass, M., 2021. “A Comparative Study of the Thermal Performance of Plastic Bottle Wall against Traditional Composite Brick Wall Typologies”, Journal of Construction Research 2.

[15] Abouhadid, M.; Mansour, A.; Shafik, R.; ElRawy, O., 2019. “Thermal Performance of Plastic Bottles Walls Reused in Building Construction for Waste Reduction”, International Journal of Innovative Technology and Exploring Engineering (IJITEE) 9.

[16] Adaji, M.U.; Adekunle, T.O.; Watkins, R.; Adler, G., 2019. “Indoor comfort and adaptation in low-income and middle-income residential buildings in a Nigerian city during a dry season”, Building & Environment 162, 106276.

[17] Hashemi, A.; Cruickshank, H.; Cheshmehzangi, A., 2015. “Environmental impacts and embodied energy of construction methods and materials in low-income tropical housing”, Sustainability 7, 7866–7883.

[18] Adefila, A.; Abuzeinab, A.; Whitehead, T.; Oyinlola, M., 2020. “Bottle house: utilising appreciative inquiry to develop a user acceptance model”, Built Environment Project and Asset Management 10, 567–583.

[19] Adefila, A.; Chen, Y.F.; Chao, C.M.; Oyinlola, M.; Anafi, F., 2022. “Developing transformative pedagogies for transdisciplinary education – Resources and competencies students need”, Innovations in Education and Teaching International, 1–12.

[20] Roberts, B.M.; Beizaee, A.; Onyenokporo, N.; Oyinlola, M., 2023. “Upcycled construction materials to reduce dwelling overheating in tropical climates: The bottle house”, Building & Environment, 2023, 110183.

[21] Martinez-Molina, A.; Boarin, P.; Tort-Ausina, I.; Vivancos, J.L., 2017. “Post-occupancy evaluation of a historic primary school in Spain: Comparing PMV, TSV and PD for teachers’ and pupils’ thermal comfort”, Building & Environment 117, 248–259.

[22] Sharifi, S.; Saman, W.; Alemu, A.; Boland, J., 2021. “A proposed long-term thermal comfort scale”, Building Research & Information, 2021, 49, 661–678.

[23] BS EN ISO 7730, 2005. “Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria”, 2005.

[24] ASHRAE, A., 2010. “Standard 55-2010: Thermal environmental conditions for human occupancy”, American Society of heating, Refrigerating and Airconditioning Engineers: Atlanta, 2010.

[25] Shin, H.; Kang, M.; Mun, S.H.; Kwak, Y.; Huh, J.H., 2021. “A study on changes in occupants’ thermal sensation owing to CO_2 concentration using PMV and TSV”, Building & Environment 187, 107413.

[26] Abubakar, I.R., 2014. “Abuja city profile”. Cities 41, 81–91.

[27] World Climate Guide, n.d. “Abuja Climate Guide, Nigeria”. http://www.worldclimateguide.co.uk/guides/nigeria/abuja/?units=metric&style=symbols (accessed Oct. 17, 2021).

[28] Testo, 2023. “Norm-compliant comfort measurement with the testo 480”, Testo Ltd 2023. Available from: https://www.testo.com/en-UK/products/testo-480-iaq (accessed Mar. 09, 2023).

[29] Climate Data, 2023. “Abuja climate: Average Temperature, weather by month, Abuja weather averages”, Climate-Data.org. Available from: https://en.climate-data.org/africa/nigeria/federal-capital-territory/abuja-703/ (accessed Mar. 09, 2023).

[30] Fanger, O., 1972. “Thermal comfort”, McGraw-Hill book company, New York, 1972.

[31] de Dear, R.J.; Brager, G.S., 2002. “Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55”, Energy & Buildings 34, 549–561.

[32] Fanger, P.O.; Toftum, J., 2002. “Extension of the PMV model to non-air-conditioned buildings in warm climates”, Energy & Buildings, 2002, 34, 533–536.

[33] Feriadi, H.; Wong, N.H., 2004. “Thermal comfort for naturally ventilated houses in Indonesia”, Energy & Buildings, 2004, 36, 614–626.

[34] Hamzah, B.; Gou, Z.; Mulyadi, R.; Amin, S., 2018. “Thermal comfort analyses of secondary school students in the tropics”, Buildings 8, 56.

[35] Broday, E.E.; Moreto, J.A.; de Paula Xavier, A.A.; de Oliveira, R., 2019. “The approximation between thermal sensation votes (TSV) and predicted mean vote (PMV): A comparative analysis”. International Journal of Industrial Ergonomics 69, 1–8.

[36] Fang, Z.; Feng, X.; Lin, Z., 2017. “Investigation of PMV model for evaluation of the outdoor thermal comfort”, Procedia Engineering 205, 2457–2462.