ASSESSMENT OF THERMAL COMFORT IN NATURALLY VENTILATED CLASSROOMS IN THE TROPICAL SAVANNA CLIMATE OF NIGERIA

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by

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LIST OF ABBREVIATIONS

AAV	Air Movement Acceptance Vote
AC	Air-Conditioned
AMV	Actual Mean Vote
aPMV	Adaptive Predicted Mean Vote
APV	Air Movement Preference Vote
ASHRAE	American Society of Heating, Refrigerating and Airconditioning Engineers
ASV	Air Movement Sensation Vote
CBE	Center for the Built Environment
CEN	Comit´e Europ´een de Normalisation
Clo	Clothing
cPMV	Corrective Predicted Mean Vote
DBS	DesignBuilder Software
DBT	Dry Bulb Temperature
ePMV	Extension of predicted mean vote
FCT	Federal Capital Territory
HPV	Humidity Preference Vote
HSV	Humidity Sensation Vote
ISO	International Standard Organization
ITC	Indoor Thermal Comfort
NV	Naturally Ventilated
PET	Physiological Effective Temperature

PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPD new	Predicted Percentage of Dissatisfied New
R2	Coefficient of Determination
RH	Relative Humidity
SET	Standard Effective Temperature
SPSS	Statistical Package for the Social Sciences
Ta	Air Temperature
TA	Thermal Acceptance
TC	Thermal Comfort
Tcomf	Comfort Temperature
TCV	Thermal Comfort Vote
Tg	Globe Temperature
Tn	Neutral Temperature
TnG	Griffiths Neutral Temperature
Top	Operative Temperature
TSS	Thermal Sensation Scale
TSV	Thermal Sensation Vote
Tw	Wet Bulb Temperature
Va	Air Velocity

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PENILAIAN KESELESAAN TERMA DI DALAM BILIK DARJAH BERPENGUDARAAN SEMULA JADI DI IKLIM SAVANA TROPIKA NIGERIA

ABSTRAK

Isu perubahan iklim dan kecekapan tenaga di dalam bangunan telah menjadikan penyelidikan berkaitan keselesaan terma semakin signifikan. Peningkatan suhu yang disebabkan oleh perubahan iklim memberi kesan terhadap tahap keselesaan dan kesihatan penghuni bangunan, terutamanya kanak-kanak sekolah yang terdedah kepada keadaan terma dalaman yang kurang selesa. Oleh itu, kajian ini bertujuan untuk menyiasat persepsi pelajar terhadap persekitaran terma dalaman dan menentukan keadaan terma optimum di dalam bilik darjah dengan pengudaraan semula jadi di iklim savana tropika di Abuja, Nigeria. Bagi mencapai matlamat ini, dua kajian lapangan dan simulasi bangunan telah dijalankan untuk menilai keselesaan terma dan persepsi penghuni, yang melibatkan 2758 responden daripada 83 bilik darjah pada musim kering dan lembap. Responden terdiri daripada 2,739 pelajar sekolah menengah dan 19 guru yang telah dipilih daripada empat (4) sekolah menengah di Abuja. Kajian kes yang dipilih mewakili pelbagai pengguna dalam persekitaran iklim yang setara dengan Abuja. Data yang diperoleh melalui tinjauan adalah pengukuran fizikal, simulasi pemboleh ubah keselesaan terma dan soal selidik jawapan persepsi penghuni terhadap iklim dalaman. Sehubungan itu, data tersebut telah disimpan di dalam lembaran data dan tertakluk kepada analisis statistik deskriptif dan inferensi menggunakan perisian analisis SPSS versi 23 dan Microsoft Excel. Penilaian tersebut mendapati hanya 27.3% daripada kajian kes bilik darjah dan 21.9% daripada penghuni memenuhi kriteria keselesaan ASHRAE Standard 55 yang ditetapkan oleh American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). Di samping itu, 59% daripada penghuni mendapati keselesaan terma bilik darjah adalah diterima. Walau bagaimanapun, 70% daripada penghuni juga telah memilih keadaan yang lebih sejuk. Kajian mendapati julat suhu selesa bagi bilik darjah tersebut adalah antara 26.5 ℃ dan 30.9 ℃, dengan suhu neutral 28.7 ℃. Perbandingan analisis telah dijalankan antara Min Pilihan Sebenar (AMV) dengan Jangkaan Min Pilihan (PMV) bersama-sama PMV dari simulasi Komputer. Dapatan kajian menunjukkan bahawa PMV secara amnya telah melebihkan sensasi terma pelajar dan PMV yang diperhatikan telah mengurangkan nilai suhu neutral sebanyak 4.2K manakala simulasi PMV mengurangkan nilai suhu sebanyak 3.9K. Kesimpulannya, dapatan kajian ini berfungsi sebagai saranan yang berguna untuk reka bentuk keselesaan terma dan penilaian di dalam bilik darjah dengan berpengudaraan semula jadi di Abuja, Nigeria.

ASSESSMENT OF THERMAL COMFORT IN NATURALLY VENTILATED CLASSROOMS IN THE TROPICAL SAVANNA CLIMATE OF NIGERIA

ABSTRACT

Issues of climate change and energy efficiency in buildings have made thermal comfort research increasingly significant. The rising temperature caused by climate change impacts building occupants' comfort level and health, especially school children exposed to unfavourable indoor thermal conditions. Therefore, this study aims to investigate students' perceptions of the indoor thermal environment and determine the optimum thermal condition in naturally ventilated classrooms in the tropical savanna climate of Abuja, Nigeria. In achieving this aim, two field investigations and building simulations were conducted to evaluate the occupants' thermal comfort and perceptions, involving 2758 respondents from 83 classrooms during the dry and wet seasons. The respondents encompass a total of 2,739 secondary school students and 19 teachers selected from four (4) secondary schools in Abuja. The selected case studies represented a range of users in an equally comparable climatic environment with Abuja. The data collected in the surveys were fieldwork measurements, simulation of thermal comfort variables, and questionnaire answers of occupants' perceptions of the indoor climate. Accordingly, the data were stored in a spreadsheet and subjected to descriptive and inferential statistical analysis using the analytical software programs SPSS version 23 and Microsoft Excel. The assessment revealed that only 27.3% of the case-studied classrooms and 21.9% of the occupants meet the ASHRAE Standard 55 thermal comfort criteria stipulated by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). Subsequently, 59% of the occupants found classroom thermal comfort conditions acceptable. However, 70% of the occupants also would have preferred it to be cooler. The study finds a comfort temperature range for the classrooms between 26.5°C and 30.9 ^{o}C and a neutral temperature of 28.7 ^{o}C. A comparative analysis was conducted between the Actual Mean Votes (AMV) with the observed Predicted Mean Votes (PMV) and the computer simulated PMV. The result suggests that the PMV generally overestimates students' thermal sensation and that the observed PMV undervalues the neutral temperature by 4.2K while the simulated PMV undervalues it by 3.9K. In conclusion, the findings serve as a valuable recommendation for thermal comfort design and assessment in naturally ventilated classrooms in Abuja, Nigeria.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The chapter serves as an introduction to the study. It begins with a discussion of the research background and provides a brief literature review of previous related studies. It further discusses the problem statement, the objective of the research, and research questions that are derivable from the research's objectives. This is followed by a description of the study's scope, limitations, and significance. Finally, the chapter concludes with a summary of the chapters.

1.2 Research Background

The surge in urbanisation, climate change, and the increase in living standards and economic development significantly impacted global energy consumption (Allouhi et al., 2015; Liu et al., 2023). In addition to the perennial upsurge in global energy consumption, many developing countries are currently facing an energy crisis because of their inability to cope with their energy requirements. This shortage has resulted in inadequate supply, load shedding, and erratic power supply. To stop this trend, we must save energy in the areas that use the most energy (i.e energy consumption in buildings) (López-Pérez, Flores-Prieto, & Ríos-Rojas, 2019).

The building sector is the largest energy end-use sector (Huo, Ma, Xu, Feng, & Cai, 2022). It accounts for 40–50% of the energy consumption for electricity or heat. It is also responsible for about 20–40% of the final energy consumption in developing countries (Wenninger, Kaymakci, & Wiethe, 2022). Heating, ventilation, and air-conditioning (HVAC) are the main energy end-use (Krajčík, Arıcı, & Ma, 2023). It contributes to about half of the overall building energy use (Jung, 2019; Yang, 2019). There is, therefore, a pressing need to develop a new strategy to enhance comfort in buildings without compromising energy sustainability (Ochedi & Taki, 2022).

Some moderation and practical solutions have been recommended to reduce the present and projected upsurge in temperature in the built environment and dampen energy consumption in buildings. The control includes advocacy for the greening of urban areas (Yahia, Johansson, Thorsson, Lindberg, & Rasmussen, 2018), modification of building /surface materials, and urban morphology (Coutts, White, Tapper, Beringer, & Livesley, 2016), insulation of buildings (De Gracia & Cabeza, 2015; Hassan & Al-Ashwell, 2015) and improving and regulating thermal comfort in buildings by passive and active means (Azmi, Baharun, Arıcı, & Ibrahim, 2023; Borghero, Clèries, Péan, Ortiz, & Salom, 2023; López-Pérez et al., 2019; Yuan et al., 2022)(Abd Rahman, Haw, Fazlizan, Hussin, & Imran, 2022). (Yuan et al., 2022) affirmed that indoor thermal comfort significantly impacts a building's energy efficiency and occupants' satisfaction.

With the pressing need to reduce energy consumption's environmental and economic costs, studies covering several aspects of indoor thermal comfort have attracted authors for many decades. Among these are the development of models and indices (Arakawa Martins, Soebarto, & Williamson, 2022; Barone et al., 2023), the conduct of field surveys (Costa, Freire, & Kiperstok, 2019; Yuan & Ryu, 2022; López-Pérez et al., 2019), the conduct of experiments in climate chambers (Luo, Wang, Brager, Cao, & Zhu, 2018); and establishing thermal comfort standards and evaluation methods (Arakawa Martins et al., 2022; Barone et al., 2023). The most important findings currently serve as the foundation for national and international standards. The energy a building uses will decrease if people understand thermal comfort and follow the standards (Lamsal, Bajracharya, & Rijal, 2023).

Thermal comfort is a mental state expressing satisfaction with the thermal environment (ASHRAE Standard 55, 2020). It describes the synthesised feeling of the body's thermal state (Holopainen et al., 2014). Thermal comfort inside buildings is attained when indoor environmental conditions satisfy 80% of the occupants (ASHRAE Standard 55, 2020). It is practically impossible to satisfy all the occupants'" comfort. Fundamentally, scholars differ in determining a general thermal comfort theory. Each researcher has an exclusive comfort zone because it varies from person to person (Allam, 2012). But many researchers agree that there are four environmental factors (temperature, thermal radiation, humidity, and airspeed) and two other personal factors (activity and clothing) affecting how people perceive the temperature (Ali & Al-Hashlamun, 2019; Q. Zhao, Lian, & Lai, 2021)

Over the decades, extensive research on thermal comfort has led to two key approaches: the thermo-physiological "(the rational or heat-balance approach)" and the "adaptive comfort approach" (ASHRAE, 2017a; M. Humphreys, Nicol, & Roaf, 2015). The rational approach supports its theory with data from climate chamber investigations "(best characterised by the works of Fanger)" (Humphreys et al., 2015; Qavidel Fard, Zomorodian, & Korsavi, 2022). On the other hand, the adaptive approach uses data from field studies (Malik & Bardhan, 2023; Mustapha, Hassan, Abdul Nasir, & Onubi, 2022; Qian, Leng, Chun, Wang, & Zhou, 2023). Both methods form the basis for existing thermal comfort standards, such as the "Thermal Environmental Conditions for Human Occupancy by the American Society of Heating, Refrigeration, and Air Conditioning" (ASHRAE Standard 55, 2020) and specifications of conditions for thermal comfort by the “International Standard Organization” (ISO7730).

In recent years, the indoor environment has caught the attention of scientists and the general public (Acero, Ruefenacht, Koh, Tan, & Norford, 2022; Kumar, 2022; Lei et al., 2022; Shrestha & Rijal, 2023; Speight, 2020;) . It is an environmental factor with a significant impact on health and well-being (Hu et al., 2022; Jian, Liu, Pei, & Chen, 2022; Lala, Murtyas, & Hagishima, 2022; Ledesma, Nikolic, & Pons-Valladares, 2022; Miranda, Romero, Valero-Amaro, Arranz, & Montero, 2022) . In this regard, the indoor environment deserves special consideration because, in modern society, a man spends a significant part of his life indoors. According to Geng, Ji, Lin, and Zhu (2017) and Sudarsanam and Kannamma, (2023), indoor thermal comfort is one of the primary factors affecting the health of people who spend between 80 to 95 per cent of their lives indoors.

An increasing frequency of complaints about an uncomfortable indoor climate shows that humans have become more sensitive to their surroundings and, as a result, are more likely to complain about the workplace's indoor climate, over which they have little or no control. As a result, there is an increasing understanding and interest in examining the impact of the indoor environment on inhabitants. Field studies show that many of these criticisms can be traced to undesirable thermal conditions (Mustapha, Hassan, Abdul Nasir, & Onubi, 2022). Realising that good indoor thermal conditions in buildings help to improve occupants' comfort, many countries have standards and guidelines for the design of systems to provide physical conditions suitable for thermal comfort (Barbhuiya & Barbhuiya, 2013).

According to previous studies, the public worries about the indoor school environment for two main reasons: school buildings are more prone to environmental difficulties than other buildings because recurring budgetary challenges contribute to insufficient facility operation and maintenance (Cui, Cao, Park, Ouyang, & Zhu, 2013). In addition, children spend more time in school than in any other indoor location except their homes (Jastaneyah, 2023; Mustapha et al., 2023)

Among all types of buildings, educational buildings, particularly primary and secondary schools present an exceptional ground for experimentation on indoor thermal comfort because they are the first model of public building people are familiar with. Apart from being the locus of education, the school buildings also play a central role in communities' lives as they encourage sustainability by providing the building envelope for tutoring younger generations. Essentially, a school represents a sustainable building prototype model of good practice for children and the community. The occupational density of school buildings also offers an excellent opportunity for architects and engineers to investigate and apply thermal comfort knowledge and strategies to help raise students' awareness from the early stages. Pérez-Lombard, Ortiz, and Pout (2008) found that much energy is used to ensure people are comfortable with the temperature in a building. Studying the building's thermal conditions is necessary to reduce energy consumption.

Naturally ventilated buildings broadly use passive cooling strategies to create a comfortable indoor climate (Hamzah et al., 2020; Subhashini et al., 2021); in contrast, air-conditioned buildings rely on active cooling. Natural ventilation is limited in providing thermal comfort because it depends on daily weather conditions (Abd Rahman et al., 2022; Etheridge, 2015). Nevertheless, it offers more adaptive opportunities for the occupants (Shrestha & Rijal, 2021, 2023). As a result, residents in naturally ventilated buildings are more tolerant to changes in the daytime and seasonal temperatures. This condition contrasts with those who live in air-conditioning buildings, who are unhappy when temperatures change in ways they did not expect. Conversely, studies have shown more complaints in buildings with air-conditioning than in naturally ventilated buildings (Jian et al., 2022).

In Nigeria, traditional buildings are naturally ventilated and have high thermal capacity. In return, this condition provides a relatively acceptable level of thermal comfort. The facilities are often equipped with a courtyard, adaptable shading devices, and appropriate orientation and are ventilated naturally. While traditional buildings provide good thermal comfort, their conventional construction methods are no longer in vogue due to changes in the standard of living and behaviour (Bouden & Ghrab, 2005). On the other hand, most recent buildings are poorly operated, especially from a thermal comfort point of view. Traditionally, building design relied on cross-ventilation and mechanical ventilation by fans to achieve thermal comfort. As living standards rise and people become increasingly affluent, a higher expectation of building facilities' standards is anticipated. Therefore, it is exciting to note that most classrooms in Nigeria rely on cross-ventilation and mechanical ventilation by fans to achieve thermal comfort. However, a new crop of classroom buildings with air conditioning systems has begun to emerge. This condition warrants further investigation.

A close observation of Federal Capital City (FCC) Abuja school facilities revealed that about half of the territory's privately-owned schools are air-conditioned. - indifference to public schools that relied on a combination of cross-ventilation and mechanical ventilation by fans to achieve thermal comfort. Some see the migration from mechanical ventilation to air conditioning as showcasing affluence or ego than one of necessity. This is because it is not based on established empirical evidence.

Literature review suggests that most thermal comfort research considerations in Nigeria and elsewhere have always been given to office and commercial buildings compared to other structures, such as educational buildings. This is because previous comfort studies were most commonly related to workplace productivity (Djamila, 2017; Van Hoof, 2008). However, studies on indoor thermal comfort in classrooms are considered critical because of the high occupancy density. Students naturally spend more time in the classroom than in any other space except their homes (Angelova & Velichkova, 2022; Maknun, 2021). Assume that schools and classes provide a comfortable place for students, students will learn more and improve their academic achievement and performance. Because of the high occupants density in classrooms and the negative influence an unsuitable thermal environment can have on teaching, learning, and performance, it has always been critical to provide a guideline on thermal comfort conditions in educational buildings (Barbhuiya & Barbhuiya, 2013; A D. James & Christian 2012). In the realisation of the above, this study seeks to provide empirical data on thermal comfort from schools in the tropical savanna climatic region of Nigeria about the range of conditions for which occupants in the classrooms are thermally comfortable.

1.3 Previous Related Studies

Several field studies have already been undertaken on thermal comfort in educational spaces. The developing picture is complex, but certain similar themes point to the need for more research into whether and which criteria are appropriate, and which must be enhanced. Thermal comfort temperature determination in diverse climates ranging from temperate to tropical has taken a substantial portion of thermal comfort research in recent decades. Most of them have recently been collated and categorized in two comprehensive studies by Zomorodian et al. (2016) and Singh et al. (2019). Most of these studies established that the students' preference for temperature was outside what is usually considered an acceptable temperature range.

Webb, (1959) monitor and analyse thermal comfort in an equatorial (tropical) climate. The study investigated 20 people who had lived in Malaya for a long time. Relying on wind speed data and dry and wet bulb temperatures, he derived an “equatorial comfort index” (ECI). However, this index did not consider the clothing values (Clo) or activity level as independent parameters.

Busch (1990) conducted a field investigation of over 1100 Thai office workers in two “air-conditioned” and two free-running buildings in Thailand. The term "free-running" refers to allowing the building to operate naturally and efficiently, utilizing the resources of the surrounding environment rather than heavily relying on active mechanical systems. The comfort temperature for the free-running and air-conditioned buildings was 28.5 and 24.5 °C (ET), respectively. The result is similar to the findings of the field experiment conducted by De Dear, Leow, and Foo (1991) in free-running high-rise housing and air-conditioned office buildings in Singapore. De Dear et al. (1991) discovered that occupants' comfort temperatures in air-conditioned and naturally ventilated buildings were 24.2 and 28.5 ^{o}C respectively. De Dear reasoned from this evaluation that the European office populace had the same air conditioning needs as the Southeast Asian office workers.

Kwok (1998) investigated thermal comfort conditions in Hawaii's naturally ventilated and air-conditioned classrooms. It was discovered that the neutral temperatures for the two types of classrooms were 26.8 and 27.48 ^{o}C, respectively. This contradicts the findings of De Dear et al. (1991) and Busch (1990), who discovered that free-running buildings have greater comfort temperatures than air-conditioned buildings.

A field survey was conducted by Wong and Khoo (2003) in mechanically ventilated (Fans) classrooms in Singapore in 2002 to establish their thermal conditions. The methodology adopted involved physical measurements of thermal comfort parameters while a survey of residents' opinions of the classrooms' indoor thermal conditions was conducted. The investigation revealed that none of the classes met the thermal comfort requirements of ASHRAE Standard 55. Nonetheless, inhabitants judged the temperature range outside their comfort zones acceptable. A new PMV model reducing activity pace and expectation (two common forms of adaptation) also showed inconsistency in forecasting actual thermal sensation, particularly at lower temperatures. He concluded that classroom occupants accepted cool thermal sensations more readily than warmer ones in the survey.

Ogbonna and Harris (2008) investigated thermal comfort in Jos, a mountainous city in the tropical savanna of Nigeria. Data gathered includes temperature, humidity, CO_2, lighting level, and occupants' thermal comfort sensation. The findings indicate an operative temperature of over 26 ^{o}C and a PMV neutrality that is significantly greater than the direct votes, validating findings by earlier researchers regarding the PMV value's limitations for predicting thermal comfort in free-running buildings (Fergus Nicol, 2004).

A field study was also carried out at St. Andrews Junior High School in Madina, Accra, Ghana (James & Christian, 2012). The study investigates students' perceptions of comfort and classroom thermal conditions. When the results were compared to ASHRAE's guidelines, it was observed that although many students accepted their overall thermal conditions, they still voted below the ASHRAE standard of 80 percent. The study also revealed that respondents in tropical countries such as Ghana might have a better tolerance for temperatures surpassing the summer comfort zone by 1 to 5 degrees Celsius. The finding agrees with the recommendation of Nicol (2004) and Ogbonna and Harris (2008).

In November 2017, in the sub-provincial city of Xi'an in China, Liu, Yang, Jiang, Qiu, and Liu investigated the thermal comfort and perceived air quality of students in a naturally ventilated university classroom under a prevailing low ambient outdoor air temperature of approximately 10 °C (Liu, Yang, Jiang, Qiu, & Liu, 2019). Based on the 992 responses that were assessed, the comfort temperature was 20.6 °C, and the preferred temperature was 22.78 °C. When the indoor operational temperature was between 18.3 and 23.8 °C, less than 10 per cent of occupants were dissatisfied. The Adaptive Predictive Mean Vote (aPMV)[China's thermal comfort model for free-running structures] gave a higher comfort temperature.

Vellei, Herrera, Fosas, and Natarajan (2017), in their investigation, demonstrate that current adaptive standards provide a straightforward linear relationship between indoor comfort and outdoor temperature. It is assumed that this adequately explains the effects of all other variables, including relative humidity (RH) and air velocity. Given its well-known effect on comfort, the absence of a relative humidity indicator is particularly odd. Using a meta-analysis of summary data, a new relative humidity-inclusive adaptive model was developed that greatly expands the range of acceptable interior conditions for developing low-energy, naturally conditioned buildings around the world.

Lau, Zhang, and Tao (2019) examine the thermal comfort of users of educational spaces on a tropical university campus using three different ventilation systems (air conditioning, hybrid ventilation, and natural ventilation). He discovered that hybrid spaces had considerable advantages over natural ventilation and air-conditioning areas in terms of a greater proportion of neutral thermal sensation votes, temperature satisfaction, and overall thermal comfort. The findings in hot and humid areas give compelling evidence in favor of natural ventilation and hybrid learning spaces. These ventilation solutions can make the temperature more comfortable and minimise the energy consumed for cooling and the CO2 emissions that result from it.

Fabozzi and Dama (2019) conducted a field study in Milan in both free-running and air-conditioned university classrooms at Politecnico di Milano during the summer of 2017 in 16 classrooms. The study evaluated 985 pupils' responses using Fanger's and adaptive models in accordance with ANSI/ASHRAE Standard 55-2017 and EN 15251:2007 standards. The result was further compared to the 'students' thermal comfort perceptions. The result shows that the adaptive model in free-running classrooms was appropriate for forecasting students' comfort zones according to the ASHRAE standard 55. On the other hand, the comfort temperatures that EN 15251 suggested were not good enough for most of the students.

Ali and Al-Hashlamun's (2019) study evaluates the indoor thermal climate in various prototype Jordanian school structures. The research evaluates and compares the effects of envelopes in un-insulated and thermally insulated school blocks using field monitoring and simulation. During peak hours, the results indicate that both schools surpassed the range of acceptable levels. But the temperature inside the school that had insulation was better than that inside the school that did not.

Buonocore, De Vecchi, Scalco, and Lamberts (2020) conducted a field study in So Luis, Brazil, to determine the preferred and optimum temperature parameters in the hot and humid equatorial climate. The experiment was conducted in "air-conditioned" and "naturally ventilated" classrooms. Environmental factors were monitored concurrently with administering thermal assessment questionnaires to undergraduate students. There was a significant difference between the preferred and acceptable thermal sensations, reflected in the preferred and comfort temperatures. In air-conditioned classrooms, the optimal thermal conditions were between 23 and 24 °C above the standard effective temperature. More than 20% of students were uncomfortable at temperatures below 22 °C due to excessive cold when clothing insulation values were close to 0.3 clo. In addition, the results demonstrated that indoor air temperatures might be set as high as 26 °C without compromising thermal comfort.

1.4 Problem Statement

Previous literature in many studies suggests that indoor thermal comfort (ITC) has a significant impact on the long-term viability, energy consumption, and occupant satisfaction of a building (Ayegbusi and Yola, 2022; Kapoor et al., 2021; Maina, Abba, and Abba, 2016; Mohamad Zamri, Ismail, and Md Ajis, 2019; Munonye & Ji, 2021; Rodríguez, Coronado, & Medina, 2021; Rodriguez and D'Alessandro, 2019; Sharma, Raman, Yadav, Khan, and Yadav, 2022; Wargocki, Porras-Salazar, and Contreras-Espinoza, 2019; Zhao, Lian, and Lai, 2021). Additionally, some of these studies demonstrated that thermally inadequate spaces negatively impact occupants' general health and well-being and contribute to the sick building syndrome (Al-Khatri, Etri, and Gadi, 2022; Al horr et al., 2016; Song, Mao, and Liu, 2019). Based on these facts, the study of indoor thermal comfort (ITC) in buildings has received significant academic research attention since the end of the last century (Acero, Ruefenacht, Koh, Tan, & Norford, 2022; Amith, Joshi, & Siddegowda, 2022; Schweiker, 2022).

Most of these studies have been conducted in regions outside the tropics, especially in the northern hemisphere, including Asia and Ocenia regions (Guevara, Soriano, and Mino-Rodriguez, 2021; Korsavi, Jones, & Fuertes, 2022; Singh et al., 2019). Incidentally, most of the world's largest and fastest-growing cities are in developing nations subjected to tropical climatic conditions (Rodriguez and D'Alessandro, 2019). It has been projected that before 2050, the tropics will be home to half of the world's population (Harding, McComiskie, Wolff, Trewin, and Hunter, 2015). A search of Scopus and Google Scholar databases in 2018 revealed that only 2.3% of the scholarly literature regarding thermal comfort is associated with the tropics (Rodriguez and D'Alessandro, 2019). This represents a severe gap in research on thermal comfort studies because the tropics account for about 40% of the earth's surface. In the tropics, only a few investigations have been conducted in the African sub-region, with Tropical Africa emerging as the region with the least research on ITC worldwide (Rodriguez and D'Alessandro, 2019). Enescu (2017), Mustapha, Hassan, Khozaei, and Onubi, (2023) and Yau and Hasbi (2013) attested to the general lack of knowledge and information on thermal comfort in tropical Africa and made a case for more testing and studies in the area. The central problem to be researched by this study is to address the shortage of data on ITC in the tropics, especially in the African sub-continent. As a basis for the study, the problem is four-fold.

Firstly, there is a general absence of thermal comfort guidelines explicitly addressing the indoor thermal environment of educational buildings and classrooms. Christhina Cândido, de Dear, and Lamberts (2011) shows that, for 49 years (1969–2018), only 93 published papers generally relate to classroom thermal comfort. A review of related literature suggests that architects and engineers approach the design of educational buildings in the same way as other public structures. They are compelled to rely on existing standards such as ISO7730 and ASHRAE Standard 55 as references (S. Carlucci, Bai, de Dear, & Yang, 2018; Huang, Huang, Lin, & Hwang, 2015; Huang & Hwang, 2016; Martinez-Molina, Boarin, Tort-Ausina, & Vivancos, 2017; Stazi, Naspi, Ulpiani, & Di Perna, 2017; L. Yang et al., 2014; Y. H. Yau & Chew, 2014). These standards are inadequate because they were designed for a steady-state office setting in which clothing and activity levels, as well as occupant density in space, were considered constant (Djamila, 2017; Singh et al., 2019). It is worth noting that this trend is prevalent not only in developing countries but also in developed countries' classrooms (H. Yun et al., 2014; Zomorodian et al., 2016).

In Nigeria, there is an overall dearth of studies on thermal comfort in Nigerian towns compared to other nations with comparable population densities (Rodriguez and D'Alessandro, 2019)(Mustapha, Hassan, Khozaei, & Onubi, 2023) . On July 3, 2022, a general bibliometric search in Google Scholar, Science Direct, Web of Science, Scopus, and SAGE journals with the terms "thermal comfort and Nigeria" and thermal comfort and the major Nigerian cities of "Bauchi, Lagos, Abuja, Kano, Kaduna, Akure, Enugu, Ibadan, and Port Harcourt" yielded a total of 81 documents. Only eleven (11) documents were found to be relevant to educational contexts, and none were specifically related to secondary school settings. This is potentially a significant gap and the rationale for this investigation. There is, therefore, the need to bridge the existing gap by undertaking research in high-density buildings such as classrooms to reduce the shortfall. This problem is partly resolved by answering the questions. What are the thermal conditions in a typical classroom in Abuja, Nigeria, and do the conditions comply with the criteria of ASHRAE Standard 55?

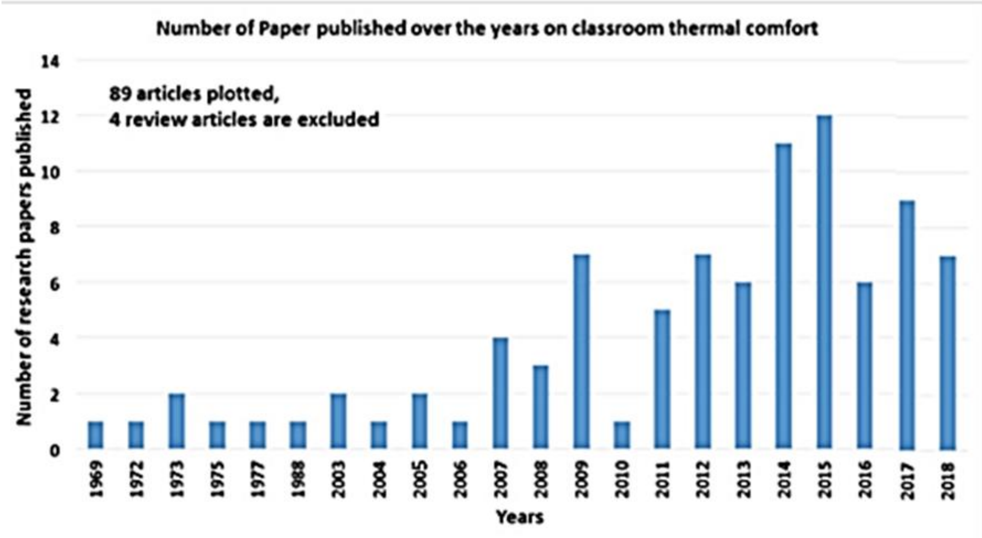

Figure 1.1 Number of published papers on thermal comfort
Source: (Singh et al., 2019)

Secondly, in Nigeria, traditionally, classrooms depend on cross ventilation and, later, a combination of cross ventilation and fans to improve thermal comfort (C. Munonye & Ji, 2021). As environmental technology is improving, living standards increase, and people want the most excellent interior environment possible. A higher anticipation of the standard of educational facilities is expected. It is remarkable to observe that the landscape of Abuja has recently been dotted with multinational private schools with air-conditioning classrooms. In contrast, public schools persist with the traditional mode of ventilation. The change from a fan-assisted natural ventilation model to air-conditioning may be based on self-esteem, as the shift is not based on empirical evidence. Empirical research into student perceptions of thermal comfort in naturally ventilated classrooms is required to determine the adequacy of naturally ventilated classrooms in Abuja in providing comfort for the students. Consequently, it is appropriate to ask, "What are naturally ventilated classroom occupants' impressions of thermal comfort, and at what thermal state are they comfortable?"

Thirdly, to achieve thermal comfort and reduce energy costs in buildings, standards such as ANSI/ASHRAE Standard 55 and "specifications of conditions for thermal comfort by the International Standard Organization (ISO7730)" are used. The data behind these international standards have been partly obtained through the heat balance and the adaptive comfort model (Fergus Nicol et al., 2012). The practicability and applicability of the PMV model have been questioned, especially on its geographical application range and application in different types of buildings (De Dear, Kim, & Parkinson, 2018; Tartarini, Cooper, & Fleming, 2018; G. Y. Yun, Kong, & Kim, 2012).

Similarly, some of the adaptive comfort field research also indicated that building inhabitants find the indoor thermal condition to be satisfactory, while thermal sensation votes (TSV) surpassed the value specified by ASHRAE Standard 55 (Gou, Gamage, Lau & Lau, 2018; Hamzah, Gou, Mulyadi & Amin, 2018; James & Christian, 2012; Yan, Mao & Yang, 2017). It is, therefore, appropriate to inquire, "How well do the predictive models of comfort match the observed subjective responses from a naturally ventilated classroom in Abuja?" The answer will help validate the two thermal comfort models in a naturally ventilated classroom in Nigeria and explore the results in line with the continuous modification of the thermal comfort standards.

Finally, to achieve thermal comfort in buildings, thermal comfort standards are implemented in the design and construction of buildings. These standards set out the exact physical conditions that must be met to create a thermally conducive environment (ASHRAE Standard 55, 2020). The Nigerian National Building Code was recently approved (the review is still ongoing) to provide guidelines for the design and construction of buildings in Nigeria. However, the code does not address the issue of students' and schools' thermal comfort. Accordingly, it is important to undertake research on thermal comfort in students and schools to provide building code reviewers with some helpful information regarding children and classroom standards for thermal comfort.

1.5 Research Questions

i. What are the thermal conditions in a typical naturally ventilated classroom in Abuja?

ii. How well do the thermal conditions in the classrooms meet the requirement set by ASHRAE Standard 55?

iii. What are the respondents perceptions of the level of thermal comfort in the classrooms?

iv. What is the optimal temperature in the classrooms in Abuja?

v. How well do the predictive models of comfort match the observed subjective responses?

vi. What are the thermal comfort settings applicable to classrooms in the study area

1.6 Research Objectives

The research objectives are as follows:

i. To investigate the classrooms' indoor thermal environment in Abuja and identify whether the conditions comply with the criteria of ASHRAE Standard 55

ii. To evaluate thermal comfort perception from the classroom respondents and the optimal temperature in the classrooms

iii. To determine how well results from the models that predict thermal comfort match up with the observed answers from the respondents (subjective responses).

iv. To recommend thermal comfort settings applicable to classrooms in the study area.

Table 1.1 shows the association between the research problem, research questions, research objectives, and Research Methods

Table 1.1 Illustrates the connections between the research problem, the research questions, the research objectives, and the research methods

Research Problem	**Research Objectives**	**Research Questions**	**Research Methods**
Lack of studies on thermal comfort in classrooms in the tropical savanna climate of Abuja It is also unknown if the classroom conditions comply with the criteria of ASHRAE Standard 55. (Ogbonna & Harris, 2008; Singh et al., 2019)	Objective 1 To investigate the classrooms' indoor thermal environment in Abuja and identify whether the conditions comply with the criteria of ASHRAE Standard 55	Question 1 What are the thermal conditions in a typical naturally ventilated classroom in Abuja? Question 2 How well do the thermal conditions in the classrooms meet the standard set by ASHRAE Standard 55	Quantitative Method Physical measurement and computer simulation using DesignBuilder software. Descriptive statistics .
There are no published studies on the thermal comfort perception of classroom occupants in the tropical savanna region in Nigeria. (Singh et al., 2019).	Objective 2 To evaluate thermal comfort perception from the classroom respondents and the optimal temperature in the classrooms	Question 3 What are the occupants' perceptions of the level of thermal comfort in the classrooms? Question 4 What is the optimal temperature in the classrooms?	Respondents Survey method (Descriptive statistics) Inferential statistic (Regression)

Table 1.1 (Continued)

Research Problem	Research Objectives	Research Questions	Research Methods
It is unknown how the predictive models of comfort relate to the observed subjective responses in a naturally ventilated classroom in Abuja.	Objective 3 To determine how well the results from the models that predict thermal comfort match up with the answers from respondents,	Question 5 How well do the predictive models of comfort match the observed subjective responses?	Quantitative Method Compare objective (measurements) and subjective (Questionnaire) Inferential statistics. Pearson correlation
There is no available guideline on thermal comfort for students and classrooms in the area (Akande & Adebamowo, 2010; C. Munonye & Ji, 2021)	Objective 4 To recommend a guideline applicable to classrooms in the study area	Question 6 What is the thermal comfort guideline applicable to classrooms in the study area?	Quantitative Method Make recommendations based on findings from objectives 1 to 3.

1.7 Scope and Limitation

i. Scope

This research evaluates indoor thermal comfort in classrooms in the tropical savanna climate of Abuja, Nigeria, using fieldwork and computer simulation approaches. This study is limited to naturally ventilated classrooms in Abuja. In terms of case studies, the study's scope is limited to secondary schools and their students and teachers as respondents. The geometry or overall shape of the classrooms studied is restricted to standard rectangular-shaped classrooms with 20 to 70 students. Measurements of classroom indoor environmental parameters are also limited to "air temperature, air velocity, mean radiant temperature, and air humidity". The scope of this research is illustrated in Figure 1.2.

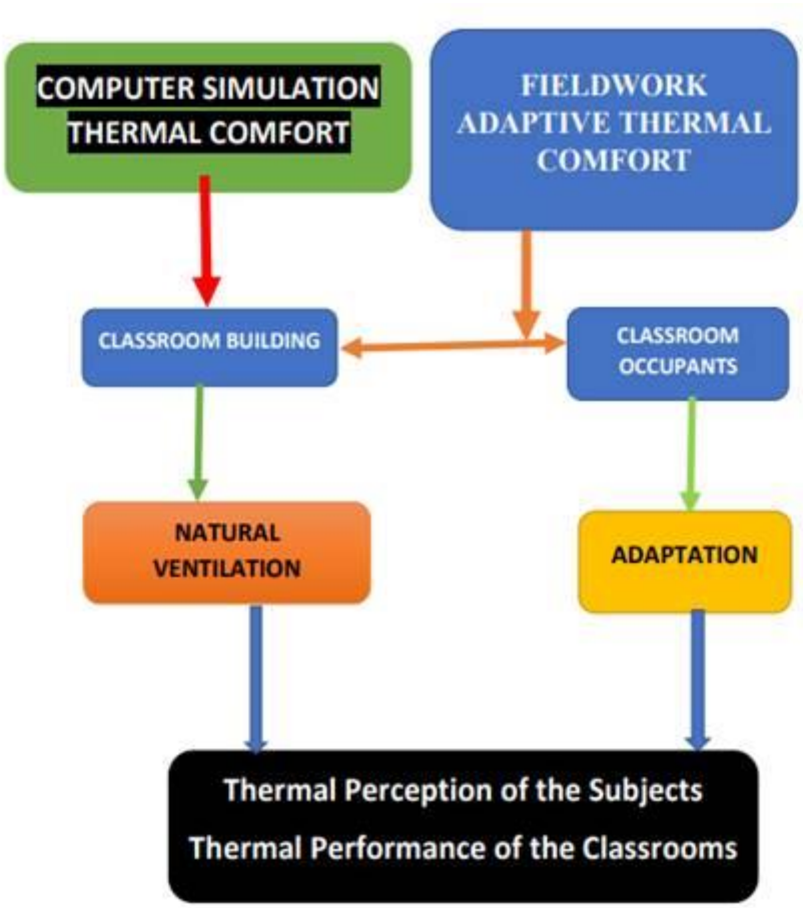

Figure 1.2 Scope of the research

ii Limitations

This study is important for comprehending how school children in Nigeria's hot and humid climate of Abuja perceive their thermal comfort. However, it is not without its limitations:

1. This study was originally set up to investigate indoor thermal comfort in naturally ventilated and air-conditioned classrooms in Abuja However, due to the coronavirus outbreak, school authorities revoked authorization for fieldwork in air-conditioned classrooms.
2. The precision of computer simulation programs (DesignBuilder) significantly relies on the accuracy of the weather data, which is not

site-specific and the ability to specify and duplicate all the features and characteristics of the real world in the model (which is error-prone).

1.8 Research Framework

The research framework for this research is organized into three parts, namely:

1. Phase 1: Review of Literature
2. Phase 2: Research Methodology
3. Phase 3: Analysis of the Data

Figure 1.3 displays the study framework's flowchart.

Phase 1 deals majorly with background reading (literature review) to establish a gap in the body of literature. Based on the gap discovered, a research title is formulated from relevant keywords. The research objectives and questions are then derived from the research problem statement.

In phase 2, field measurements involving objective (physical measurement of environmental parameters) and subjective assessment (perception measurement with the aid of a questionnaire) are conducted to assess occupants' thermal comfort in classrooms. Simulation of selected case study classrooms was also done for triangulation of results. Data acquired in phase 2 is analysed in phase 3 to obtain results.

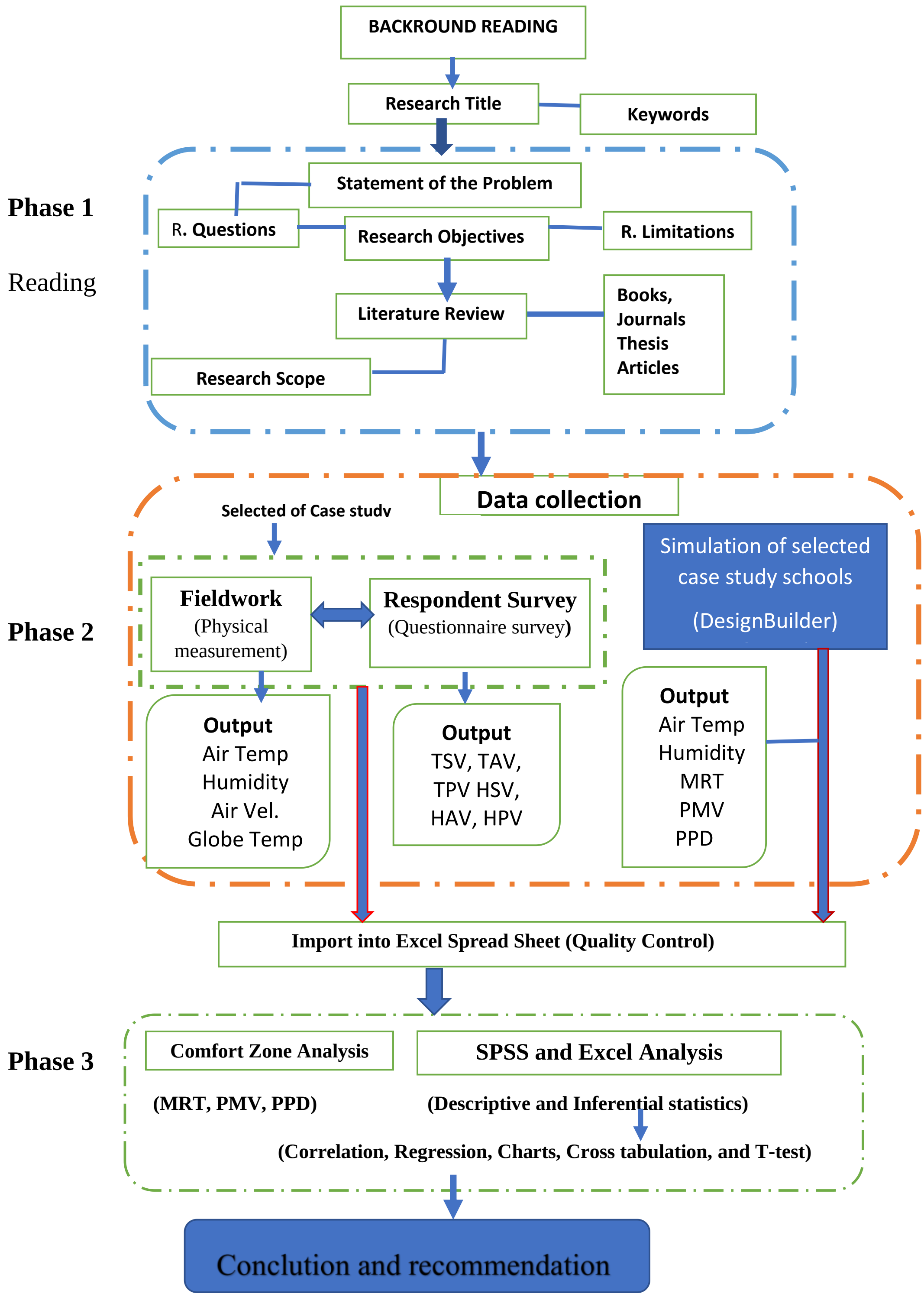

Figure 1.3 The research framework

1.9 Significance of the Study

This research's long-term significance is to promote a more sustainable building environment without compromising inhabitants' thermal comfort. This study will therefore aid in the drive against future energy crises and global warming. The findings of this research could further help in the following ways:

i. The study suggests thermal comfort guidelines for naturally ventilated classrooms in Abuja and, by extension, the study climatic zone. This extended range could help form a new thermal standard for local classroom building design.

ii. Given the alarming proportion of private schools in Abuja that rely on air conditioning systems to offer thermal comfort, The need for energy conservation in secondary school buildings warrants this investigation. Due to the association between thermal comfort and energy preservation in buildings, the study has shown that adaptation in naturally ventilated classrooms is a crucial energy conservation factor.

iii. The study also extends the literature on thermal comfort in classrooms to the tropical savannah climate of the west African subregion, which has not received much attention in earlier research.

iv. The results of this research are likely to have practical implications for stakeholders in the building industry. Data from this research may establish foundation data for classroom thermal comfort and related studies in the country. They can influence the design of new buildings and the evaluation of thermal comfort in existing structures.

v. It will provide a further understanding of the working process of adaptive thermal comfort, which will be beneficial to users and designers. Occupants can obtain more specific knowledge to achieve thermal comfort and energy conservation. Concurrently, architects and engineers can produce better design strategies and standards to meet the occupant's desire for thermal comfort in the climatic research zone.

vi. This research output will also contribute to the staff and student's health and well-being in the short and long run. The findings will help improve student academic performance (there is a strong correlation between thermal comfort and academic performance).

vii. The methods and findings of the research conducted in Abuja and the study climate zone can assist similar climate zones and other countries in studying thermal comfort and designing classrooms.

viii. Finally, the Nigerian National Building Code's recently approved draft (review is still ongoing) does not address the issue of children and school thermal comfort. The results of this study may give building code reviewers some helpful information regarding the standards for thermal comfort.

1.10 Summary of the Chapters

The research is divided into six (6) chapters as follows:

i. Chapter One: Introduction

The chapter discusses the research background, previous related studies, and the problem statement. It further outlines the research questions derived from the research problem to arrive at the research objectives. The study's scope, limitations,