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Future-proofing next-g homes: Enhancing thermal comfort and building energy performance through landscape integration

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Abstract

Buildings in the tropics are increasingly exposed to intense solar radiation and heat gains that result in extreme thermal discomfort, particularly in naturally ventilated buildings. As climate change accelerates, the Next Generation (Next-G) of housing stock must be designed and integrated with future-proofing strategies to ensure indoor livability. Micro-landscape interventions such as trees, lawns and water features have been found to cool outdoor environments through shading and evapotranspiration. While several studies have explored their role in mitigating outdoor heat stress, with a focus on reducing urban heat island (UHI) effects, the impact of landscape configurations on indoor thermal comfort remains underexplored, particularly in extreme climates. This study employs dynamic thermal modelling in DesignBuilder to investigate the role of micro-landscape elements on indoor thermal performance. A three-phase hypothetical building simulation approach was adopted: (1) without landscape features, (2) with landscape features and (3) with landscape features and mixed-mode cooling. Predicted future climate data for two climatically contrasting locations in Nigeria; Jos (cold) and Sokoto (hot), were used to assess comfort and energy performance. Findings reveal that by limiting solar incidences on the building envelope, landscape elements can reduce indoor discomfort hours by up to 18% in naturally ventilated spaces. However, mechanical cooling remains vital for achieving thermal comfort under future climate extremes. A combined strategy of vegetation and cooling achieved up to a 92% reduction in discomfort hours. Yet, this comfort improvement gave rise to an increased energy demand of up to 48% for the total building and 78% for conditioned spaces. These results highlight the capacity of integrated landscape strategies to support, but not replace, active systems in future-proofing Next-G buildings for thermal resilience.

Keywords: future buildings, future-proofing strategies, micro-landscapes, next-g tropical buildings, thermal comfort

1. Introduction

The rate of urbanisation and the rapid expansion of infrastructures have led to an unprecedented increase in urban heat. This trend is largely influenced by the diminishing presence of greenspaces and the increasing dominance of buildings and paved surfaces (Priya & Senthil, 2021; Wong et al., 2021). Compared to their surrounding rural areas, cities experience more elevated outdoor temperatures, causing severe thermal stress in urban centres (Marcotullio et al., 2021). This phenomenon, commonly referred to as urban heat island (UHI) effect, poses immense challenges for comfort and building energy, especially in regions with extreme year-round temperatures. One of the drivers of thermal stress in urban developments is the scarcity of vegetation which helps regulate outdoor temperatures and reduces a building's cooling load (Aboelata & Sodoudi, 2019; Wong et al., 2021). As urban centres continue to expand globally, heat

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stress is becoming more alarming, buttressing the need for strategies that enhance both outdoor and indoor thermal comfort and energy efficiency.

Cities have become the primary spotlight of research on the impact of vegetation on indoor and outdoor thermal environments. This is not surprising, as the global population is expected to dwell in cities in the coming decades. The focus of research on cities is compelled by the concentration of people, buildings and machines, which emit excessive heat and air pollution (Taleghani et al., 2019). Vegetative elements such as trees, plants and green open spaces have been recognised for their ability to regulate microclimates, thereby alleviating urban heat (Yang et al., 2018; Zeng et al., 2022; Zhao et al., 2018). However, the extent and variation of their impacts are still evolving (Ko, 2018). More so, effective building landscape offers immense cooling benefits to the wider neighbourhood (Wu et al., 2019), since it directly influences shading and evapotranspiration; two key processes that mitigate heat (Aboelata, 2020; Lombardo et al., 2023; Meili et al., 2021; Wong et al., 2021). Nevertheless, the degree of cooling provided by vegetation varies with factors such as climate (Ko, 2018), scale and the level of intervention, whether at the building or urban level (Wong et al., 2021). As a result, understanding these dynamics is crucial for designing effective nature-based solutions.

Despite the growing body of research on energy-efficient buildings, the cooling effect provided by landscape integration has not received the attention it merits in the broader context of delivering the next generation (Next-G) housing stock. The focus of most studies largely dwells on technological solutions and operational energy systems, while natural cooling mechanisms, such as evaporative cooling using water bodies and cooling through trees and plants evapotranspiration, have been somewhat overlooked (Fei, 2024; Hami et al., 2019). Moreover, the effectiveness of greenery in controlling air temperature and reducing the heat stress of outdoor environments cannot be over emphasised, as it has been shown to significantly mitigate heat stress in buildings (Abd Rahman et al., 2022; Darvish et al., 2021). As the climate crisis intensifies, greening buildings has become a non-negotiable mitigation strategy for climate goals realisation (Wong et al., 2021). The increasing dominance of grey infrastructure such as concrete and asphalt in rapidly developing cities has suppressed the potential of green infrastructure (Morakinyo et al., 2021). Given the challenges in retrofitting existing buildings, nature-based solutions offer a suitable way of regulating building comfort and reducing energy consumption (Choi et al., 2021), especially in cities where most of the population of the world is projected to reside in the future (Santiago & Rivas, 2021).

Beyond the immediate benefit of improving indoor thermal comfort, strategically positioning landscape elements such as trees, shrubs, green roofs and water elements plays a critical role in enhancing the resilience of buildings to extreme weather occurrences. These features act as natural buffers that regulate microclimates, reduce surface and air temperature and alleviate urban heat. Consequently, they contribute to sustaining the quality of life, especially in densely built neighbourhoods, by creating more liveable outdoor spaces and reducing the psychological stress caused by elevated heat. In turn, this reduction in ambient temperatures and thermal stress can significantly lower the risk of heat-related illnesses and mortality among vulnerable groups such as the elderly and children among the urban population (Koch et al., 2020). This study seeks to examine the role of landscape features in reducing discomfort in buildings; the primary unit of urban developments, through strategic planning and location of green infrastructures like trees, lawns and pools. If buildings are thoughtfully landscaped, there is an immense potential for cooling load to be reduced and when deployed systematically, these micro-scale interventions may provide a scalable pathway for future-proofing the built environment. For Next-G buildings, designed to be adaptable and climate responsive, this approach offers a practical and scalable design frontier. In extreme future climates where conventional energy systems may falter, effective landscaping will be indispensable for ensuring comfort and efficiency for the survival of the built environment.

1.1. Aim and Objectives

1.1.1. Aim

To investigate the potential of residential landscape features in enhancing indoor thermal comfort and reducing energy demand in Next-G homes under extreme tropical climates, with a focus on developing integrated, future-proofing strategies for thermal resilience.

1.1.2. Objectives

a. To examine the effect of landscape features (trees, lawns and water bodies) on indoor thermal comfort in tropical residential buildings.

b. To compare thermal performance and energy consumption of buildings under different landscape and cooling scenarios in two distinct climates in Nigeria.

c. To assess the potential of integrated landscape elements and mechanical cooling strategies in reducing discomfort hours and energy loads in future climates.

1.2. Study Questions

a. How do different landscape configurations impact indoor thermal comfort in naturally ventilated tropical homes?
b. What is the variation in thermal comfort and energy demand between landscape-only and landscape-plus-cooling scenarios under future climate conditions?
c. To what extent can landscape features contribute to future-proofing strategies for Next-G homes in extreme tropical environments?

2. Literature Review

Greening the building landscape is widely recognised as an effective climate mitigation strategy that yields one of the most thermal and environmental benefits, particularly when combined with other building strategies like solar shading and building orientation (Sharifi, 2021). Such combinations maximise passive cooling potential and reduce reliance on active energy systems. A comfortable thermal environment is generally associated with vegetation, ground surface material, building configuration and wind flow direction and impact (Zhang et al., 2023), as these elements directly influence microclimatic conditions around buildings. The strategic planting of trees around buildings has been shown to alleviate the impact of excessive temperatures, especially in regions with extreme solar radiation (Iyaji et al., 2021). Trees serve as natural thermal buffers that help to moderate indoor temperatures by reducing solar exposure on building envelopes. According to studies by Farhadi et al. (2019) and Yang et al. (2022), optimal indoor thermal comfort is achieved through the shading effect provided by the presence of trees, which limits the impact of solar incidence on buildings. In these studies, the impact of landscape elements in reducing Physiologically Equivalent Temperature (PET) varied. For instance, PET was reduced by 9.36°C mainly by increasing vegetation presence by 10% (Farhadi et al., 2019). On the other hand, PET was reduced by 1.1°C when a water body was evaluated, and up to 1.6°C with all design approaches combined (Yang et al., 2022). This reinforces the potential of vegetative shading as a passive solution to enhance thermal comfort and reduce cooling demand in hot climates.

2.1. The Concept of Next-G Buildings

Next-generation (Next-G) buildings refer to a forward-thinking paradigm in building design and construction practices, encompassing a new wave that prioritises sustainability, resilience, energy efficiency and occupant wellbeing. These buildings are predominantly equipped with advanced features to address the evolving challenges posed by climate change, urbanisation and shifting human needs. For instance, flexible building components, renewable energy systems and integrated monitoring technologies are increasingly central to the design and operation of Next-G homes (Benavente-Peces, 2019; Hao et al., 2023; Plamanescu et al., 2023). The integration of smart systems and adaptive designs enables such buildings to be more resource-efficient, respond to environmental hazards and support user comfort across varying conditions. Certification standards like the WELL Building Standard also reflect this shift by prioritising human health and comfort at the crux of design strategies (Amy, 2019; Hao et al., 2023). Despite the recurring emphasis on technological advancement, there is growing recognition that the advancement of Next-G homes also depends on an integrated approach that factors in the role of vegetative landscape into its overall performance. Landscape features such as plants, water bodies and permeable surfaces, play a crucial role in regulating building microclimates and should not be secondary to recent innovations in future green building discourse. As Gou and Xie (2017) contend, Next-G green buildings must evolve from theatrical expressions of sustainability to biologically responsive systems that leverage passive, nature-based solutions. This ecological framing highlights the necessity for landscape-informed design to complement smart, green future buildings in delivering long-term thermal comfort and climate resilience.

2.2. Strategic Vegetation Placement for Indoor Climate Moderation

Strategically placing trees and vegetation around buildings has shown substantial thermal comfort and energy saving potentials (Ayeni et al., 2019). This effect is more pronounced when vegetation is positioned to intercept prevailing solar angles, reducing the intensity of radiation reaching the building. A study by Darvish et al. (2021) in an academic building in Iran found that well-planned tree landscape contributed to a reduction in energy consumption and a decrease in discomfort hours, consequently enhancing the overall thermal performance of the building. Furthermore, studies by Meili et al. (2021) demonstrate that the cooling effect provided by well-watered trees can reduce surface air temperature by up to 5.8 °C , although the degree of cutback is noted to differ with location. This location-dependent variability emphasises the need for context-specific planting strategies aligned with regional microclimates. Research further suggests that beyond thermal comfort, having trees and vegetation in view of building occupants enhances psychological wellbeing (Wu, 2023). Access to green views has been linked to reduced stress and improved cognitive function, making vegetation a valuable design asset for environmental design of buildings. However, vegetation in users' sight, while psychologically beneficial, must not limit daylight access and ventilation flow. Hussain et al. (2014) in this regard noted that to allow for natural light and air flow, tall trees should be avoided at the south side of the building. This is especially relevant in climates where natural daylight is a vital resource for reducing reliance on artificial lighting.

The inherent qualities of trees further impact on their ability to provide shade and cooling effects. Table 1 represents a selection of locally available trees and shrubs that can be used for landscaping compact plots, highlighting key species characteristics. According to Alexander (2021), tree height and canopy density can directly regulate wind flow and other microclimatic conditions, thereby affecting thermal comfort. This suggests that selection of trees should go beyond aesthetic value to aerodynamic considerations, which could influence convective cooling. This attribute is very important in mitigating heat dissipation limitations caused by obstructed wind movement as emphasised by Meili et al. (2021), who noted that the spacing and orientation of vegetative elements enhance the efficiency of airflow patterns around buildings. Strategically placing trees with high leaf area index (LAI) or high leaf density (HLD) is remarkably effective in providing shading and reducing solar gains (Xiao & Yuizono, 2022; Yang et al., 2022). This effectiveness is extremely critical in dense urban centres where heat loads are often intensified. Moreover, such vegetative features contribute immensely to a decrease in physiological equivalent temperature (PET), as demonstrated by Cong et al. (2022). This approach reinforces the role of trees in enhancing both perceptual and measured thermal comfort conditions.

The higher the LAI or HLD, the greater the shading potential of the tree, which has significant implications for reducing building cooling load (Rahman et al., 2020). In urban landscapes, the arrangement and configuration of trees play a critical role in enhancing the cooling effect. A study by Zhao et al. (2018) suggests that a two-tree equal interval vegetation arrangement is more effective for heat reduction and thermal comfort than a clustered tree arrangement. This points to the influence of spatial uniformity in promoting even shade distribution and uninterrupted air flow. In addition, the orientation of trees relative to prevailing winds is crucial in maximising the cooling effect, with studies by Abdi et al. (2020) suggesting that a rectangular array of trees perpendicular to prevailing winds is more effective for reducing outdoor temperature. This configuration helps direct cooler air across outdoor surfaces and towards buildings, thus complementing passive ventilation strategies and enhancing the microclimatic quality of urban developments.

Table 1 Compact Trees for Small Residential Plots

Species (Taxonomic Name)	Common Name	Nominal Height (m)	Foliage Spread (m)	Leaf Density / Shade Quality	Description	Leaf Transmittance (%)	References
Terminalia mantaly H.Perrier	Umbrella tree or Madagascar almond	10–15	5–8	Very dense, layered canopy	Excellent layered canopy for broad, cool shade; fast-growing and minimal maintenance. Best planted for street sides, driveways, and small yards. Annual pruning required to maintain shape.	Moderate (6%)	(Kimpouni et al., 2024; Owoeye & Hauser, 2023)
Monoon longifolium (Sonn.) B.Xue & R.M.K.Saunders *(formerly known as Polyalthia longifolia*)	False Ashoka Tree or Indian Mast Tree	12–20	1–2	Moderate shade, narrow but thick vertically	Tall, slim, vertical growth. Perfect for tight spaces where horizontal space is limited. Provides moderate vertical shade but less overhead coverage. Very low maintenance.	Low (4%)	(Parkar et al., 2020; Shinde et al., 2023; Taib et al., 2019; WFO, 2025)
Delonix regia (Bojer ex Hook.) Raf.	Flamboyant Tree or Flame Tree	10–15	10–18	Wide spreading, high-quality shade	Stunning bright red flowers with very wide, umbrella-like canopy. Provides excellent shade but needs more lateral planting space. Not ideal too close to buildings.	High (8–10%)	(Havaldar et al., 2024; Taib et al., 2019)
Murraya paniculata (L.) Jack	Orange Jasmine or Mock Orange	2–4	1–2	Dense small canopy, partial shade	Compact tree/shrub with dense leaves and fragrant white flowers. Great for patios, borders, and small gardens. Offers moderate shade and adds fragrance. Easy to trim into hedges.	High (~10%)	(Santhoshini et al., 2022; Taib et al., 2019)
Thevetia peruviana (Pers.) K.Schum.	Yellow Oleander or Lucky nut Tree	3–6	3–5	Light to moderate shade	Fast-growing ornamental tree with yellow trumpet-like flowers. Provides light to moderate shade. Tolerates drought well but seeds and sap are toxic, so caution is needed in residential gardens with kids/pets.	Moderate (6-8%)	(Amulu et al., 2024; Fried, 2019; Owoeye & Hauser, 2023)
Plumeria rubra L.	Frangipani or Temple Tree	5-8	4-6	Moderate density, provides patchy, dappled shade	Beautiful, fragrant flowers; best for small gardens; not ideal if you want deep, full shade. Grows relatively slow.	Moderate (~7%)	(Ramlee et al., 2023; Taib et al., 2019)
Vachellia tortilis (Forssk.) Galasso & Banfi *(previously classified as Acacia tortilis*)	Umbrella Thorn	6-9	6-9	High canopy density, wide spreading, excellent deep shade	Very drought-tolerant, ideal for hot tropical zones; forms a high umbrella-like canopy, good for roof and side wall shading. Needs space to spread.	Low (~4–6%)	(Cheruto et al., 2025; Ella et al., 2018)
Ficus benjamina L.	Weeping fig	10-15	3-6	Very dense foliage, thick, dark, cooling shade	Fast-growing, perfect for tight urban spaces; roots can be aggressive, so plant at least 1.5–2 meters away from foundations or pipes. Excellent for urban shading and air cooling.	Low (~4–5%)	(Mulyani et al., 2021; Orobator & Adahwara, 2022)

2.2.1. Deciduous and Evergreen Species in Residential Landscape

Vegetation selection plays a vital role in landscape-driven thermal regulation, especially in climates that are vulnerable to extreme heat or seasonal variability. One of the most impactful strategies is the deliberate use of deciduous and evergreen trees, each offering unique microclimatic benefits depending on their physiological characteristics and seasonal behaviour. Deciduous trees shed their leaves in the dry or cold season and are valued for their dual-season functionality. In hot climates, such trees offer solar shading benefits during the peak dry season, thereby reducing indoor heat gain and limiting the dependence on mechanical cooling systems (Del Campo-Hitschfeld et al., 2023; Park et al., 2023; Wu et al., 2024). During colder seasons, their leafless canopies permit greater solar penetration, enhancing passive solar heating and daylight benefits (Chen et al., 2025). In Nigeria, where extreme temperatures are recorded year-round, deciduous trees, due to their leaf-shedding attribute, may not be beneficial for long-term shading.

Evergreen species, on the other hand, are characterised by year-round foliage. This advantage is remarkably effective for consistent wind shielding, noise attenuation and maintaining stable cooling effects throughout all seasons (Chen et al., 2025). Their dense canopies help reduce ambient temperatures by increasing evapotranspiration (Wujeska-Klause & Pfautsch, 2020; Yin et al., 2024), improving air quality and acting as natural barriers against solar radiation (Chen et al., 2024; Liu et al., 2020). When planted along west-facing facades or exposed envelope surfaces, evergreen trees provide perennial shading, making them useful in regions with prolonged dry or hot periods (Chen et al., 2024). In Nigeria, deciduous species such as *Albizia zygia* (DC.) J.F. Macbr. and *Terminalia catappa* L. are commonly planted to provide seasonal shading, among other benefits while native evergreens like *Ficus exasperate* Vahl *and Monoon longifolium* are favoured for their aesthetic structure and constant microclimatic buffering. These species, when arranged strategically, have been observed to significantly improve outdoor thermal comfort, shield buildings from direct solar radiation and reduce glare and heat gain in indoor spaces. Studies have shown that based on local climatic profiles and phenological behaviour, a mismatch in species selection can undermine anticipated thermal performance (Morakinyo et al., 2020; Rahman et al., 2020). For example, native or drought-tolerant species often require less irrigation (better water-use efficiency), contributing to low-carbon and sustainable landscape practices (Rötzer et al., 2021).

2.3. Green and Water Features for Building's Thermal Comfort

Studies highlight that green infrastructure, such as green roofs, green facades and water bodies, can further augment the cooling benefits of vegetation around buildings. According to Bach et al. (2023), Chatterjee et al. (2019) and Priya and Senthil (2021), green roofs can effectively regulate outdoor temperatures by providing additional thermal insulation, reducing the need for over-reliance on mechanical cooling. Similarly, green facades are effective at reducing cooling loads and indoor temperatures by absorbing solar radiation through transpiration (Koch et al., 2020; Li et al., 2021; Lombardo et al., 2023; Widiastuti et al., 2020; Zhang et al., 2019), contributing significantly to improved indoor thermal comfort. These features, via their interactions with the built environment, form a critical part of integrated climate-resilient designs. For dry climates, green roofs show more potential for energy reduction and better thermal comfort than green façades (Lotfi & Hassan, 2024), further accentuating the importance of tailored design choices that can maximise environmental benefits across diverse regions.

On the other hand, water features such as pools and fountains also provide significant cooling effects by moderating surrounding air temperature, although their effectiveness is dependent on factors such as size, location on site, shape and climate conditions (Hong et al., 2023; Jandaghian & Colombo, 2024; Liu et al., 2022; Yang et al., 2018). Water bodies, when carefully located, induce evaporative cooling, benefiting both thermal comfort and local microclimatic conditions. Nonetheless, Hong et al. (2023) noted that humidity levels in the vicinity of water bodies can increase, which must be carefully managed in regions prone to high moisture levels to avoid contributing to discomfort and health risks associated with mould growth in buildings.

2.4. Climate Adaptation Potential of Green Infrastructure in Tropical Contexts

Buildings in tropical regions are more susceptible to the impacts of climate change (Méndez-Serrano, 2024), but greening buildings has been found to be a very effective strategy in reducing outdoor temperatures, especially during peak temperature hours (Chatterjee et al., 2019). In addition to reducing the cooling demands of buildings, vegetation plays a critical role in mitigating heat stress by offering shading and regulating the microclimatic conditions (Haruna et al., 2018; Jega & Muhy Al-Din, 2023). These roles not only improve comfort but also reduce the health risk associated with prolonged heat exposure. This is particularly crucial in hot and humid climates like Nigeria, where outdoor temperatures can exceed 35°C (Umar et al., 2020), making both outdoor and indoor spaces almost uninhabitable without shading or cooling interventions. In extreme climates, the growing demand for mechanical cooling, a major requirement for comfort, is not only unsustainable due to its high energy consumption, but also contributes negatively to environmental impacts (Ayeni et al., 2019; Jay et al., 2021; Lundgren-Kownacki et al., 2018). This dependence on active systems can escalate grid stress and undermine national energy goals. Cooling load in such climates accounts for a substantial proportion of carbon emissions, making energy efficiency a central role in the design of tropical buildings (Widiastuti et al., 2020). Thus, integrating passive cooling strategies such as the use of vegetation is paramount in reducing both the immediate cooling needs and long-term environmental impacts.

The potential of green infrastructure to improve the environmental quality of buildings in Nigeria has been cited by researchers (Adegun et al., 2021), but maximising its benefit can be very challenging due to perceived barriers like cost (Adewale et al., 2024), maintenance (Owolabi et al., 2020) and a lack of awareness of its potential values. As highlighted by Ayeni et al. (2019) and Iyaji et al. (2021), green infrastructure for thermal comfort enhancement in Nigeria is yet to be fully harnessed, pointing to a critical gap. Diverse mixes and configurations of landscape elements affect thermal and emotional sensations differently, with the magnitude of impact varying by season (Yan et al., 2023). Despite its recognised promise to improve environmental quality, seasonal differences in the effectiveness of green infrastructure further complicate its impact, as the cooling benefits of green spaces may vary across different seasons (Liu et al., 2022), necessitating dynamic design strategies that account for temporal fluctuations.

To date, numerous studies have focused on the influence of vegetative cover on outdoor thermal comfort and urban heat, while studies on the impact of outdoor landscapes on indoor comfort remain fragmented. Much of the existing literature has prioritised external microclimatic benefits, sometimes overlooking the crucial interconnection between landscape design and indoor thermal regulation. This gap is particularly evident in tropical regions like Nigeria, where intense solar radiation is predominant, making indoor thermal comfort extremely challenging without mechanical ventilation. Addressing this gap will be crucial for green building optimisation to improve both outdoor and indoor thermal comfort, while enhancing energy efficiency and climate resilience. An integrated approach that considers the effects of outdoor landscapes on internal environmental conditions could significantly elevate the performance and sustainability of tropical buildings.

3. Methods and Materials

3.1. Study Approach

This study adopts a simulation-based comparative approach to investigate how the integration of landscape features, especially trees, lawns and water bodies, affects indoor thermal comfort and energy efficiency in future tropical residential buildings. The use of simulation allows for a consistent and controlled assessment of design interventions that would be financially demanding to test using physical experimental setup. As Lin and Brown (2021) point out, accurately modelling microclimatic interactions can be very challenging; however, focusing on landscape elements that are both measurable and thermally influential provides a pathway for meaningful performance.

3.2. Geographic and Climate Overview of Study Locations

The study was conducted in two locations in Nigeria; Jos and Sokoto. Jos, the capital of Plateau State is located at approximately 9.8965° N, 8.8583° E (Figure 1). It is situated on the Jos Plateau in north-central Nigeria at an altitude of about 1295 meters above sea level (masl), making it one of Nigeria's highest urban settlements. This elevation contributes to its temperate microclimate, characterised by, relatively high precipitation from July to September (204 mm - 238 mm) and an annual mean temperature of between 21°C and 27°C (Figure 2), supporting a verdant environment and making it suitable for diverse landscape configurations. According to Köppen climate classification, Plateau state is classified as AW (Figure 3), a tropical wet and dry or savanna climate, with the driest month having precipitation of less than 60 mm. This is further supported by the eco-climatic map (Figure 1), which classifies Plateau State as predominantly a midaltitude and derived savanna region.

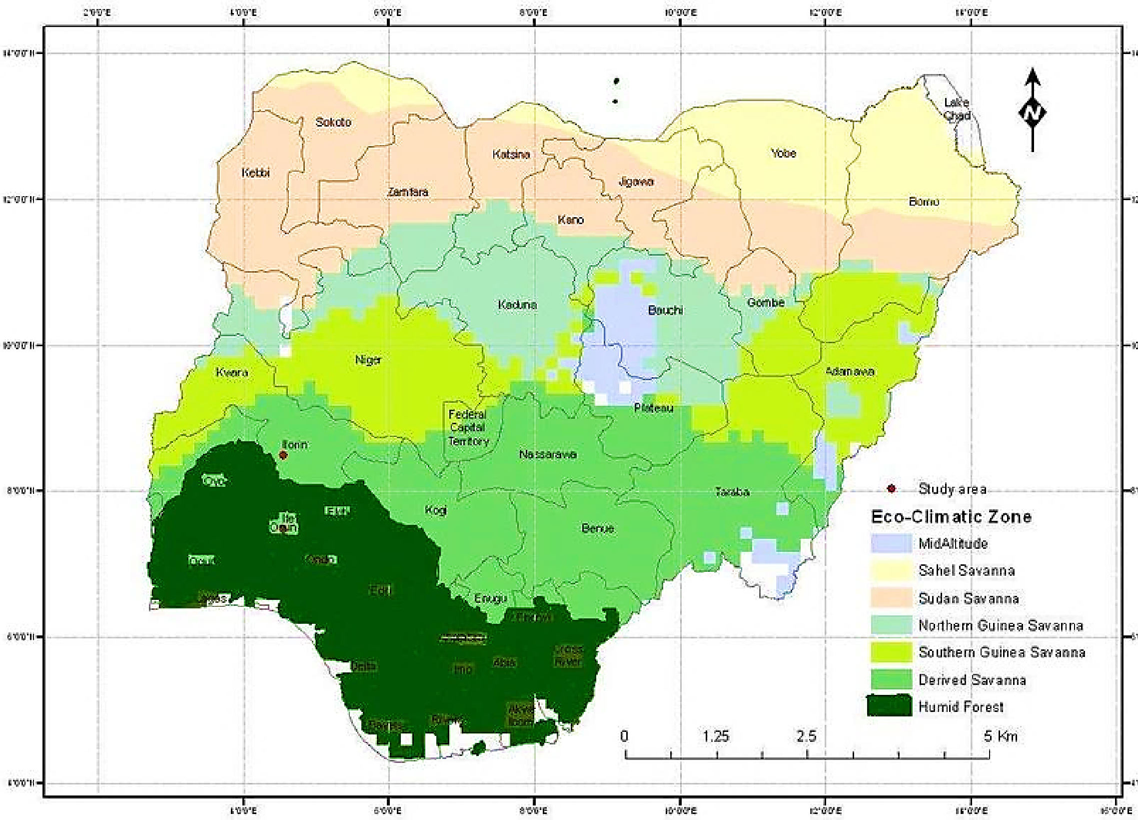

Figure 1 Map of Nigeria showing climatic zones (Source: Maps Nigeria, n.d.)

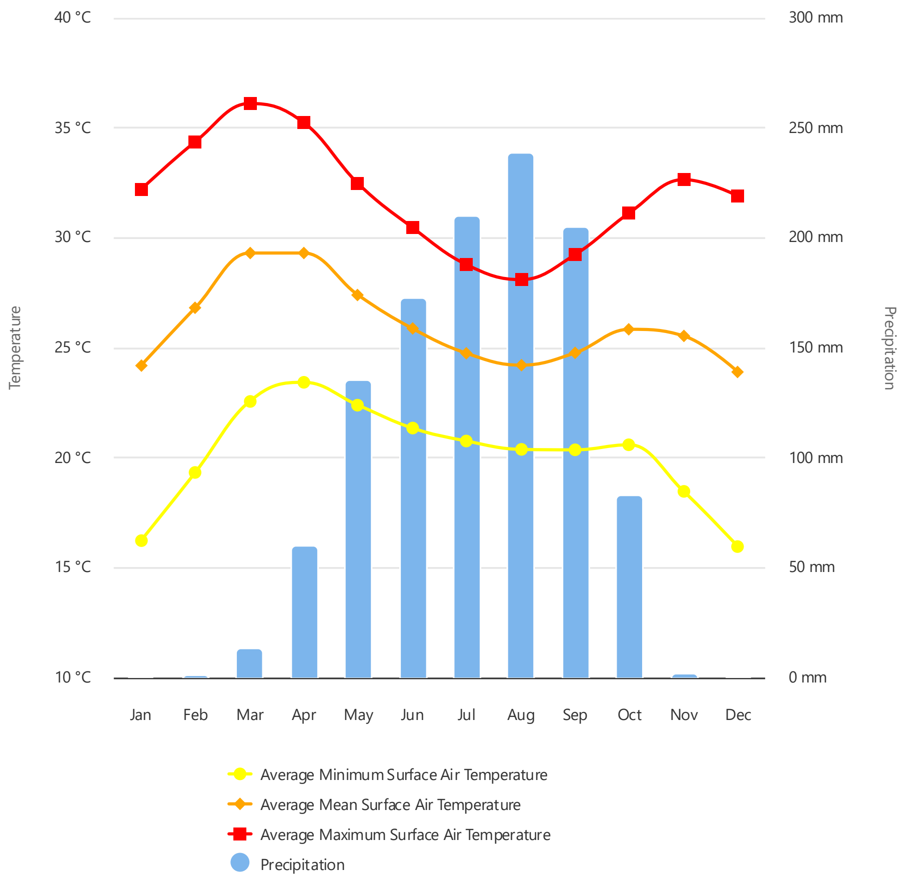

Figure 2 Monthly climatology of air temperature and precipitation 1991-2020 - Plateau, Nigeria (Source: World Bank Group, n.d.)

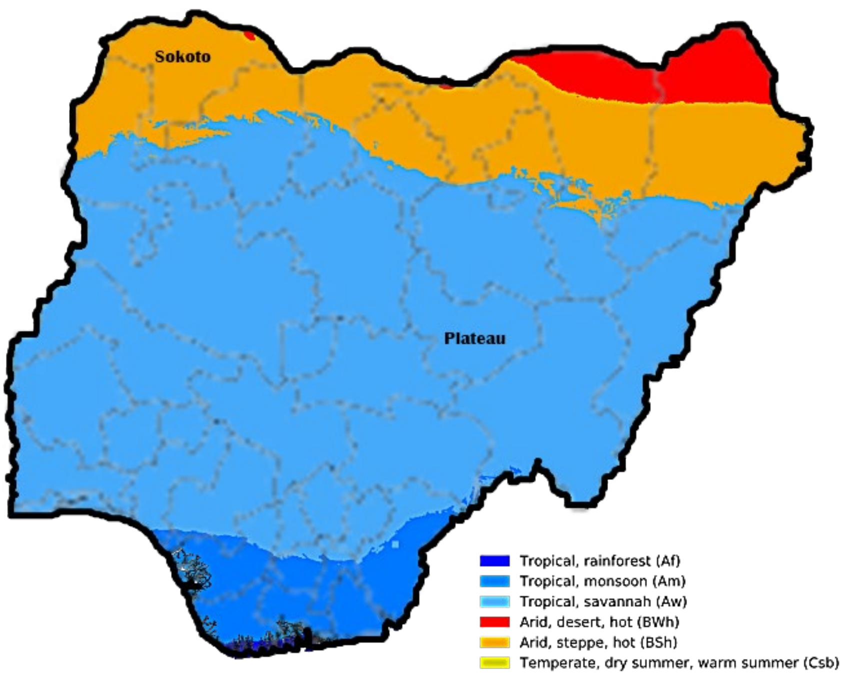

Figure 3 Map showing study locations (Base map retrieved from Beck et al., 2018, modified by authors)

In contrast, Sokoto, the capital of Sokoto state, is located around 13.0059° N, 5.2476° E. It lies within Nigeria's dry Sahelian and Sudan Savanna Zone (Figure 1), typified by an arid (Bsh) climate (Figure 3), sparse vegetation and flat terrain. With average maximum temperature exceeding 40°C

(Figure 4) during peak dry months and rainfall averaging less than 800mm, the environment is markedly harsher and leads to extreme thermal discomfort (Fatima, 2025; Gazettengr, 2025; Olayide, 2025). Urban morphology in Sokoto is compact and utilitarian, shaped historically by adaptive responses to extreme heat, necessitating the use of thick-walled buildings. These climatic and spatial contrasts between Jos and Sokoto present a valuable spectrum for analysing the role of residential garden-based landscape features in improving thermal performance in next-generation housing across different Nigerian climatic contexts.

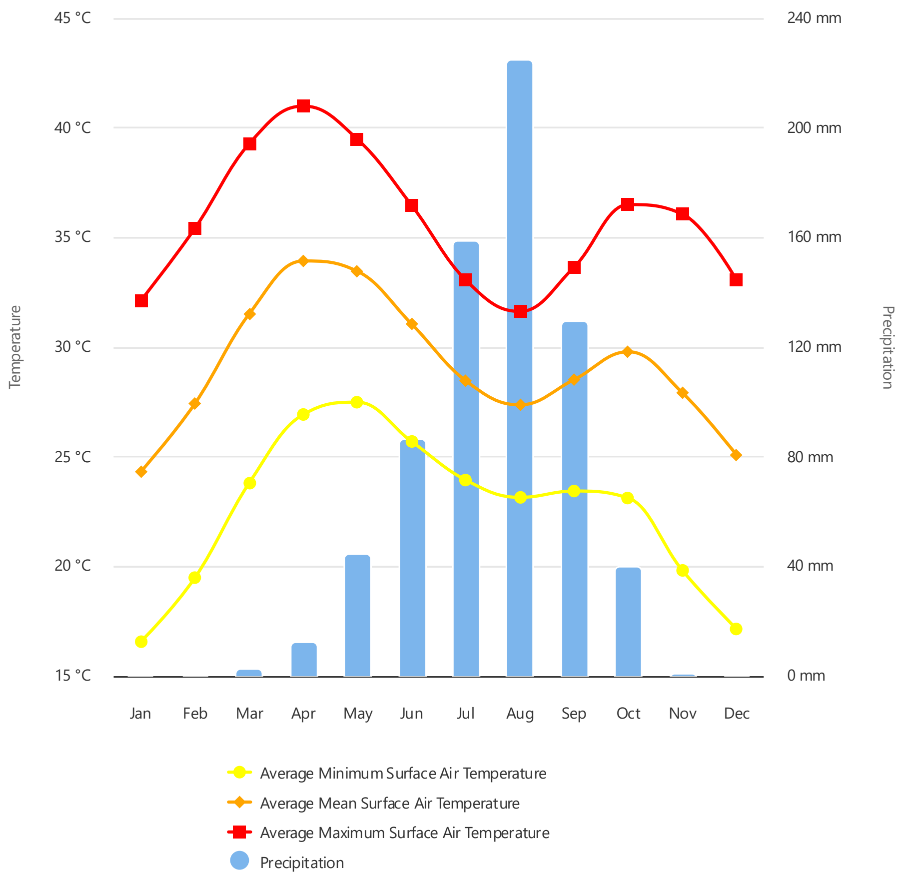

Figure 4 Monthly climatology of air temperature and precipitation 1991-2020- Sokoto, Nigeria (Source: World Bank Group, n.d.)

3.3. *Workflow*

Stage 1: Building and Landscape Modelling

A hypothetical residential building plan (Figure 5) was modelled incorporating future-proofing strategies suitable for tropical regions. These include enhanced thermal mass, exterior wall insulation, shading devices and strategic window sizing and placement (Figure 6). Landscape elements, such as trees, lawns and a water body, were introduced around the building to simulate their effects on shading and ventilation, forming the basis for subsequent thermal comfort analysis.

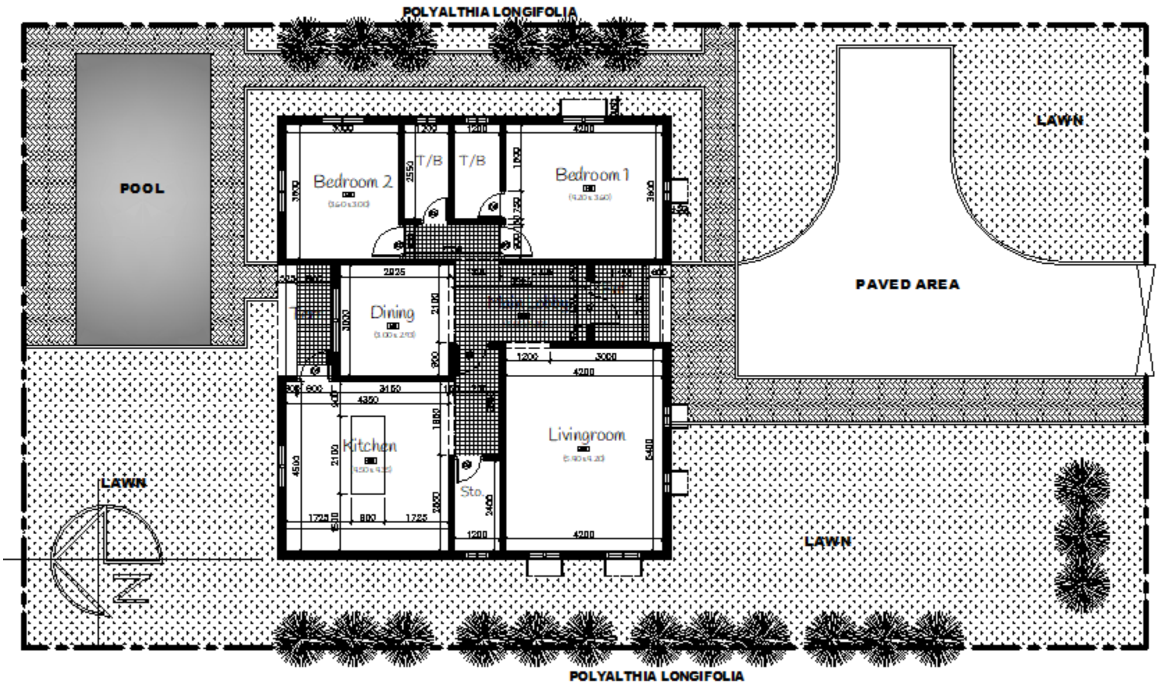

Figure 5 Building and landscape plan

Figure 6 3D view of the hypothetical test building

The building simulations were conducted using EnergyPlus weather data generated using geographical coordinates 9.897° N, 8.858° E, at an elevation of 1295 masl for Jos and 13.006° N, 5.248 ° E, at an elevation of 275 masl for Sokoto. Specific temperature data inputs for the simulations are graphically presented in Figure 7.

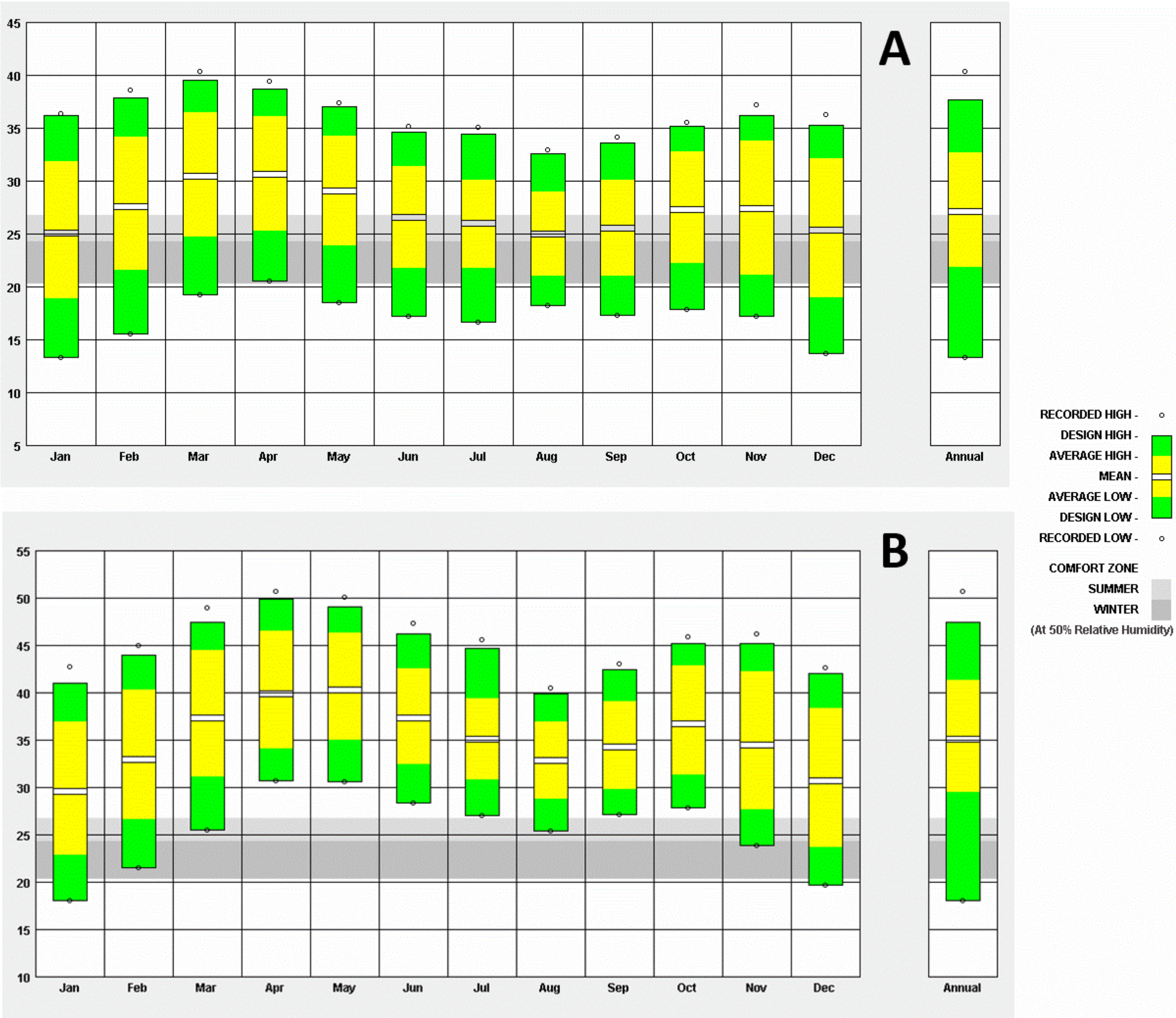

Figure 7 Temperature data for study locations: Jos (A), Sokoto (B). (Source: Climate consultant)

Design strategies such as window shading, thermal mass and evaporative cooling implemented in the design were informed by the adaptive comfort model from the psychrometric charts in Figure 8. The chart shows that cooling is expected to play a more integral role in Sokoto (59%) than in Jos (33%). Additionally, shading of windows is also significant in attaining comfort in these regions as it is needed approximately 33% of annual hours. These charts are integral in determining key strategies, in this case, cooling and shading, to ensure discomfort hours are reduced in the buildings.

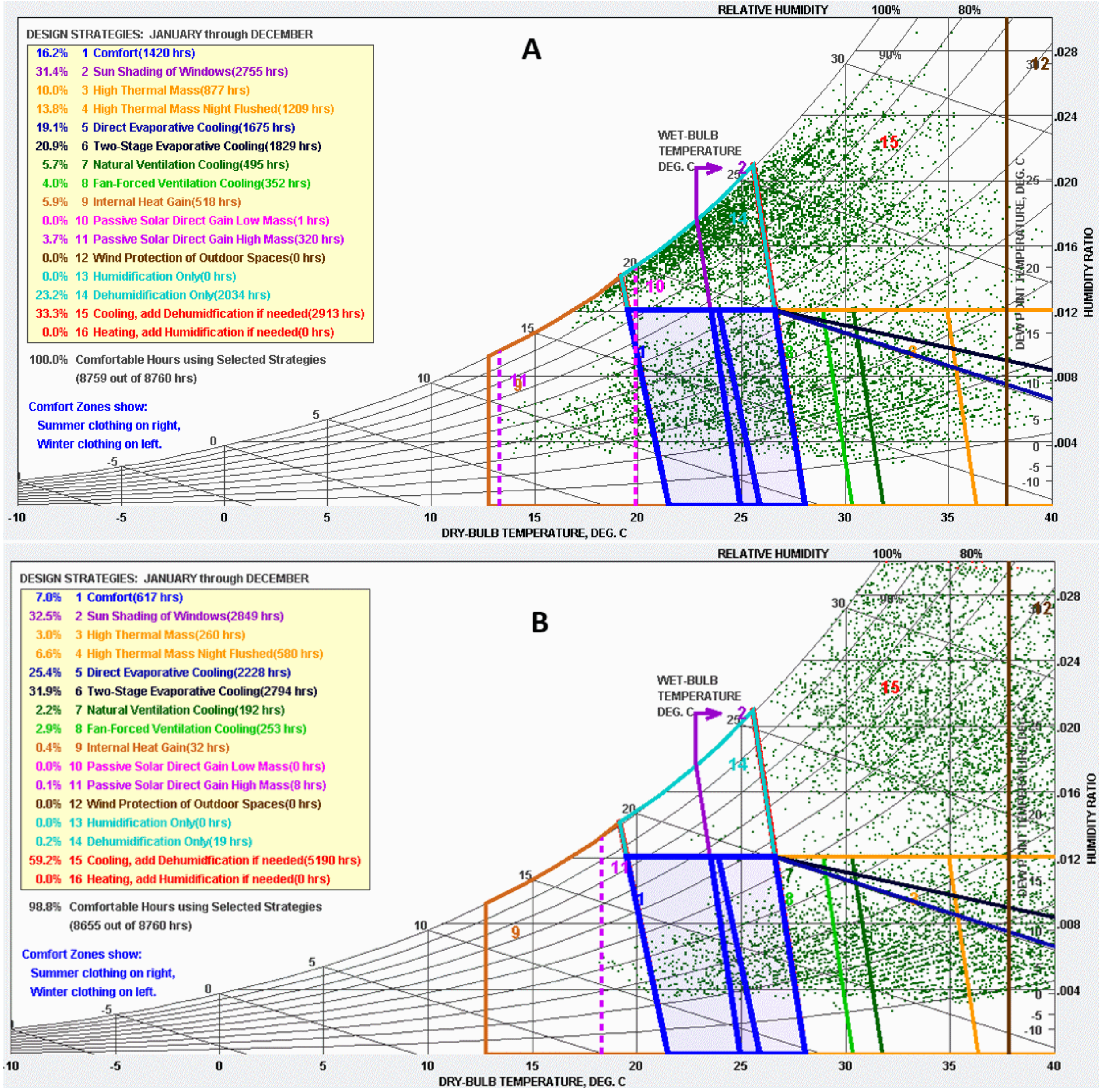

Figure 8 Psychrometric chart showing design strategies for thermal comfort in the locations: Jos (A), Sokoto (B) (Source: Climate consultant)

Stage 2: Landscape Configuration and Optimisation

Different configurations and spatial arrangements of vegetation were simulated to identify the most effective layouts for reducing indoor operative temperatures and minimising energy demands of a building within a 30 m x 15 m residential plot. These configurations were rooted in the spatial constraints of the plot's available setbacks (see Figure 5) and the prevailing South-West wind direction, which informed the strategic positioning of Mast trees (*Monoon longifolium*). The selection and placement of these trees were guided by critical landscape parameters outlined in Table 2, such as thermal conductivity, solar absorptance and canopy height, all of which significantly influence thermal interactions between landscape elements and building surfaces.

The tree's thermal conductivity of 0.2 w/m-k and high solar absorptance of 0.8 suggest that, while the canopy absorbs substantial solar energy, it transmits little heat to adjacent spaces, consequently enhancing its role in passive cooling. Additionally, the specific canopy height of 3.6 m and total height of 5.1 m were calibrated to align with the sun's trajectory during peak temperature periods for the building locations, ensuring maximum shading of east- and west-facing walls. The optimal setback of 2.1 m from the building façade was derived from solar path analysis using the

Curic Sun plugin in Sketchup (Figure 9), which permits precise visualisation of shading overlaps across seasons. These inputs were further validated through DesignBuilder's simulation environment, where exterior temperature and indoor operative temperature were continuously evaluated.

Furthermore, lawn and pool surfaces were considered as complementary landscape elements. The lawn's low conductivity (0.036 W/m-K), moderate density (1050 kg/m^3) and specific heat (1850 J/kg-k) made it effective in reducing surface heat re-radiation, thereby regulating near-ground air temperature. In contrast, the pool's higher thermal conductivity (0.6 W/m-K) and remarkably high specific heat (4182 J/kg-K) offered thermal inertia for stabilising microclimate fluctuations during peak solar hours. The absorptance properties of all elements, especially the high visible and solar absorptance (0.95) values for lawn and pool surfaces, influenced radiative interactions within the building's immediate outdoor environment. Initial vegetation layouts were developed in Sketchup using geolocation and solar analysis features to identify effective shading zones across seasonal variations. These insights were later transferred into DesignBuilder for dynamic simulation, where iterative testing of vegetation configurations provided a robust evaluation of the thermal buffering potency of landscape strategies.

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Table 2 Landscape Elements Parameters

Parameters	***Tree***	***Lawn***	***Pool***
Conductivity (w/m-k)	*0.2*	*0.036*	*0.6*
Specific Heat (J/kg-k)	*N/A*	*1850*	*4182*
Density (kg/m³)	*500*	*1050*	*998*
Thermal Absorptance	*0.9*	*0.95*	*0.95*
Solar Absorptance	*0.8*	*0.95*	*0.95*
Visible Absorptance	*0.9*	*0.95*	*0.95*
Canopy Height (m)	*3.6*	*N/A*	*N/A*
Height (m)	*5.1*	*0.15*	*N/A*

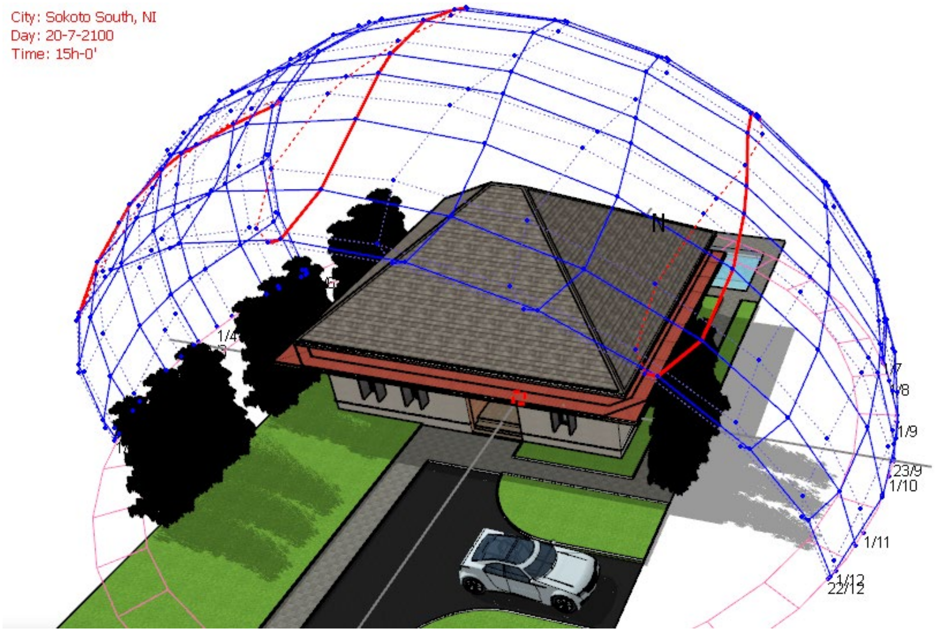

Figure 9 Test building's solar path

Stage 3: Climate-Specific Performance Assessment

The optimised landscaped building configurations were evaluated under the IPCC's extreme climate scenario (RCP8.5-2100) in two distinct locations in Nigeria: Jos, representing a cooler tropical highland climate and Sokoto, representing a hotter, semi-arid region. This comparative analysis seeks to provide insights into how variations in outdoor vegetation impact on indoor thermal performance and energy efficiency in next-generation tropical buildings under future climate conditions.

3.4. Materials and Tools Justification

Previous studies, such as Galal et al. (2020) and Darvish et al., (2021), have employed simulation tools like ENVI-Met for evaluating the environmental performance of vegetation-integrated urban environments. While ENVI-met is effective for broader urban-scale analysis, this study focuses on the building level, necessitating a more tailored simulation approach. DesignBuilder was therefore adopted for its capacity to model dynamic thermal behaviour and energy performance at a detailed building scale.

DesignBuilder's integration with the EnergyPlus engine allows for advanced simulation of passive design strategies and landscape features. Specifically, it supports the incorporation of elements such as shading devices, trees, lawns and pools using Standard and Ground component blocks, making it highly suited for assessing microclimatic interactions on indoor conditions (DesignBuilder, V7.0). To ensure accurate weather inputs, Meteonorm 8 was utilised to generate localised future weather files. The tool synthesises historical meteorological data from a vast network of weather stations and couples it with climate models to provide high-resolution climate projections. The future scenario used in this study aligns with the IPCC's Representative Concentration Pathway (RCP) 8.5 for the year 2100, representing an extreme climate outcome. According to Remund et al. (2020), Meteonorm's method of integrating statistical downscaling with General Circulation Models (GCMs) offers reliable weather data that are tailored to the selected Nigerian locations. Together, these tools permit a robust simulation of how outdoor landscapes can influence building level thermal comfort and energy consumption in extreme tropical climates.

3.5. Future-Proofing Design Strategies

To accurately reflect climate best practices in tropical residential buildings, the hypothetical building model integrates passive design features drawn from contemporary research, particularly the recommendations of Alegbe and Mtaver (2023). These strategies are aimed at reducing heat gains, enhancing indoor comfort and reducing dependency on mechanical cooling systems.

I. **Enhanced Thermal Mass**

The exterior walls were designed with a U-value of 0.517 W/m²·K, achieved through a double-wall assembly composed of concrete hollow blocks and a centrally located insulation cavity. The total thickness of this assembly is 0.35 m. This setup increases the building's thermal inertia, helping to moderate indoor temperature fluctuations by delaying heat transfer through the envelope.

II. **Exterior Wall Insulation**

A 0.05 m thick layer of lightweight Expanded Polystyrene (EPS) insulation was incorporated within the cavity wall. This material minimises conductive heat gain and contributes to maintaining thermal comfort during prolonged exposure to high ambient temperatures.

III. **Window Optimisation**

Window design and placement were tailored to take advantage of the solar orientation and wind direction. Openings on the south and west facades were reduced to 1.20 m x 0.60 m to limit solar heat gain, while those on the north and east sides were extended to 1.20 m x 1.20 m to enhance cross-ventilation potential. This asymmetrical window strategy promotes natural ventilation while managing solar ingress.

IV. **Shading Devices**

Horizontal shading projections of 1.20 m were introduced along the southern, eastern and western facades to obstruct direct solar radiation during peak periods. In addition, rooms with exposed windows on these facades feature 0.5 m vertical side fins and overhangs to further minimise solar penetration and glare. These passive shading elements are incorporated to reduce cooling loads by shielding critical envelope areas from excessive heat gain.

4. Results

The simulation results demonstrate the significant role of outdoor landscape in regulating solar gains, enhancing indoor thermal comfort and influencing energy consumption in residential buildings. A summary of the key outcomes is presented in Table 3. The findings indicate that the impact of landscape features on indoor comfort is highly influenced by the orientation of interior spaces. For example, in both Jos and Sokoto, spaces facing the north, such as Bedroom 2, the Dining area and the Kitchen, exhibited improved indoor temperature performance even in the absence of shading devices. In contrast, rooms with shading devices (e.g., roof overhangs and window fins) but oriented toward the south and west experienced higher indoor temperatures, suggesting the compounded influence of orientation and solar exposure.

Moreover, the performance of landscaped buildings varied greatly between the two locations. The cooler climate of Jos demonstrated a more moderate improvement in thermal comfort compared to Sokoto, where the semi-arid conditions amplified the benefits of landscaping. This location-specific variability aligns with the findings of Ko (2018), Meili et al. (2021) and Liu et al. (2022), who emphasise the specificity of landscape-induced thermal environments to different climatic regions. It is important to note that the recorded energy consumption remained constant across the simulated buildings before the introduction of active cooling systems. This is primarily due to the lighting fixtures, for which the energy load was already accounted, as no mechanical cooling or heating was applied during that phase of the simulation process.

Table 3 Results of Evaluated Metrics across Study Locations

Evaluated Metrics	*Sokoto*			*Jos*		
	No Landscape	*Landscaped*	*Landscaped and Cooling*	*No Landscape*	*Landscaped*	*Landscaped and Cooling*
Operative Temperature – Coldest Month (°C)	*34.62*	*33.95*	*29.51*	*32.13*	*31.44*	*28.25*
Operative Temperature – Hottest Month (°C)	*43.46*	*42.45*	*32.78*	*36.70*	*35.85*	*30.59*
Mean Annual Operative Temperature (°C)	*39.40*	*38.53*	*31.60*	*33.97*	*33.16*	*29.02*
Solar Gain Through Windows (Wh/m² x 10³)	*74.91*	*35.84*	*35.84*	*72.29*	*34.81*	*34.81*
Bedroom 1 – Operative Temperature (Hours Above 32°C)	*8619.50*	*8584.50*	*3690.50*	*6552.00*	*5980.50*	*605.00*
Bedroom 2 – Operative Temperature (Hours Above 32°C)	*8595.00*	*8461.50*	*3632.50*	*6794.50*	*5596.50*	*525.00*
Dining – Operative Temperature (Hours Above 32°C)	*8705.50*	*8614.50*	*2829.00*	*7800.00*	*6575.50*	*606.00*
Kitchen – Operative Temperature (Hours Above 32°C)	*8581.00*	*8477.50*	*3169.00*	*6555.00*	*5686.50*	*563.50*
Livingroom – Operative Temperature (Hours Above 32°C)	*8606.00*	*8577.00*	*3498.50*	*6507.50*	*6090.50*	*745.50*
Energy per Total Building Area (Kwh/m²)	*118.28*	*118.28*	*228.89*	*118.28*	*118.28*	*194.85*
Energy per Conditioned Area (Kwh/m²)	*N/A*	*N/A*	*539.37*	*N/A*	*N/A*	*459.17*
Cooling Energy (Kwh/m²)	*N/A*	*N/A*	*260.64*	*N/A*	*N/A*	*180.43*

5. Discussions

Influence of Landscape Features on Thermal Performance

Results from the simulations affirm the pivotal role of landscape interventions, particularly vegetation, in modulating and enhancing the indoor thermal environment of residential buildings in the tropics. Both locations, Sokoto and Jos, exhibited measurable improvements in thermal conditions due to landscape features, though the magnitude of the impact varied by location. Notably, by simply introducing lawns, solar gains through window openings were reduced by up to 14%, owing to their high reflectivity and low thermal mass, which helped moderate ground-level heat re-radiation. This aligns with the literature that underscores the role of surface albedo and ground treatment in lowering surface temperatures. More significantly, the inclusion of trees, specifically, Mast trees (*Monoon longifolium*), led to reductions in solar gains by up to 52%. This substantial decline highlights the effectiveness of tree canopies in reflecting direct solar radiation, while their transpiration processes also contribute to localised cooling effects, as supported by prior studies such as Yang et al. (2018) and Morakinyo et al. (2018). These biophysical interactions between vegetative elements and their microclimate environments reinforce the argument for green infrastructure as a vital passive strategy in hot climates.

However, the influence of landscape was not uniformly effective across the locations. In Jos, interior spaces oriented towards the north, namely the Dining, Kitchen and Bedroom 2, exhibited a notable reduction in discomfort hours by up to 17.6%, despite lacking direct shading interventions. This substantial improvement in indoor thermal comfort supports the findings of Darvish et al. (2021), who observed similar reductions attributed to tree-induced comfort. The observed enhancement may also be partly attributed to the favourable solar angles in northern orientations, which naturally receive less direct sunlight in tropical latitudes. In contrast, Sokoto, a hotter and more extreme climate, yielded minimal improvements in comparable spaces, with reductions in discomfort hours falling below 2% (Figure 10). This disparity demonstrates the sensitivity of landscape performance to both building orientation and regional climatic conditions, as opined by Liu et al. (2022). Furthermore, the reduction in mean annual operative temperature achieved solely through landscape was relatively modest, with 2.2% and 2.4% decreases observed for Sokoto and Jos, respectively. Although these shifts appear statistically minor, they can play a critical role in nudging thermally marginal indoor environments towards adaptive comfort thresholds, especially when reinforced with complementary passive design measures. These findings reinforce the potential of integrated landscape elements to act as a thermal buffer by intercepting and diffusing solar radiation before it reaches the building façade. This reduces heat conduction through the building envelope and mitigates the thermal load on internal spaces, which is critical in regions like Sokoto, where intense solar exposure is prevalent year-round.

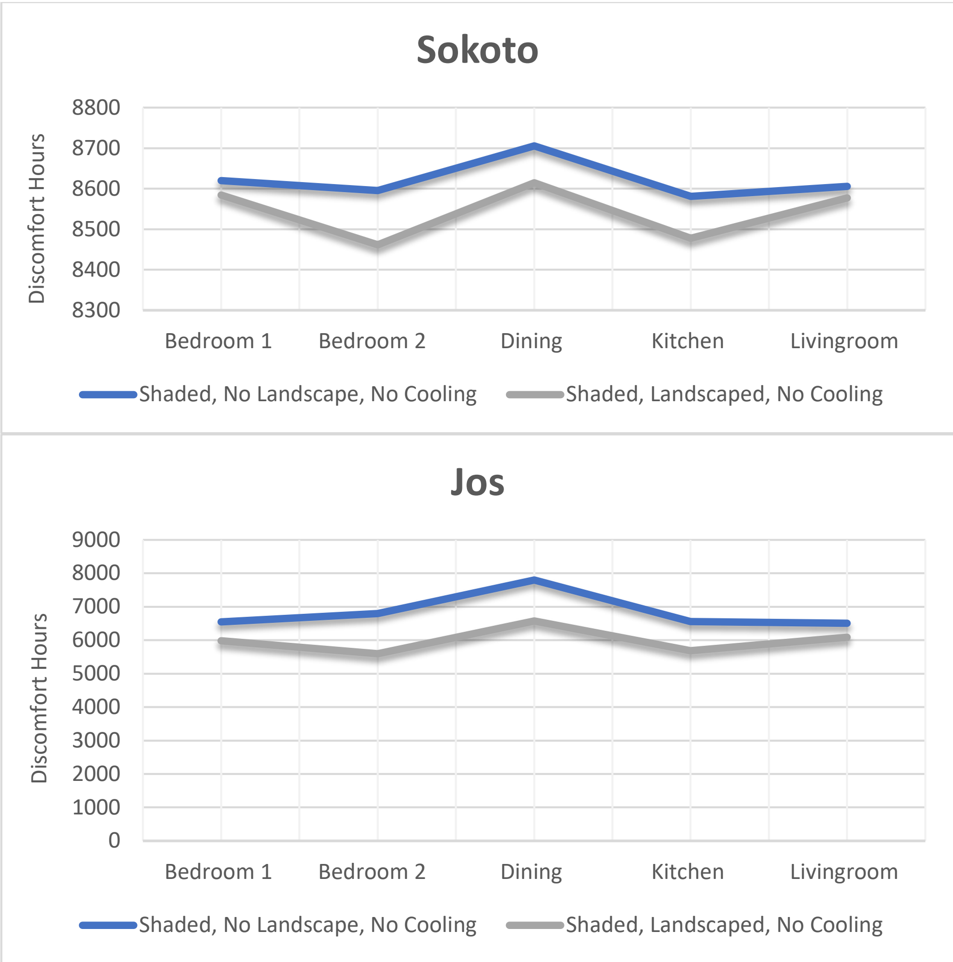

Figure 10 Impact of landscape on thermal discomfort in building spaces across the locations

Landscape and Mechanical Cooling in Future Climates

Despite the growing benefits of landscaping buildings, the results revealed that natural and passive cooling strategies alone cannot guarantee thermal comfort, particularly in the face of projected climate extremes. As observed during the hottest months; May in Sokoto (43.46°C) and April in Jos (36.7°C), outdoor temperatures surpassed the effectiveness limits of natural ventilation and vegetation-induced cooling. These extreme conditions suggest a climatic threshold beyond which passive strategies become thermally insufficient. Moreover, without mechanical intervention, indoor operative temperatures remained remarkably high for comfort, emphasising that passive-only approaches could result in significant heat stress for occupants in these climates. This supports prior assertions that, under extreme climate projections, reliance on passive strategies alone may expose vulnerable occupants to health risks linked to overheating.

However, when mechanical cooling was introduced in a mixed-mode approach (natural ventilation supplemented by scheduled air conditioning), the reduction in discomfort hours was substantial: up to 68% in Sokoto and 92% in Jos (Figure 11). These results are particularly significant for Next-G housing in tropical climates, noting that while passive landscape interventions can alleviate thermal loads, mechanical systems will remain indispensable for ensuring occupant well-being under future climate conditions. Notwithstanding, the reliance on active systems introduces a paradox, where energy consumption rose sharply for indoor comfort to be attained. Buildings without mechanical cooling had an energy use of 118.2 kWh/m², whereas, with mechanical cooling enabled, energy demand increased by 48% across the building area and 78% in conditioned spaces for the building in Sokoto. In Jos, the energy per total building area and conditioned spaces increased by 39% and 74% respectively. These surges in energy requirements across the building locations represent a critical trade-off between thermal comfort and sustainability, necessitating the need for more energy-efficient cooling technologies or adaptive control mechanisms.

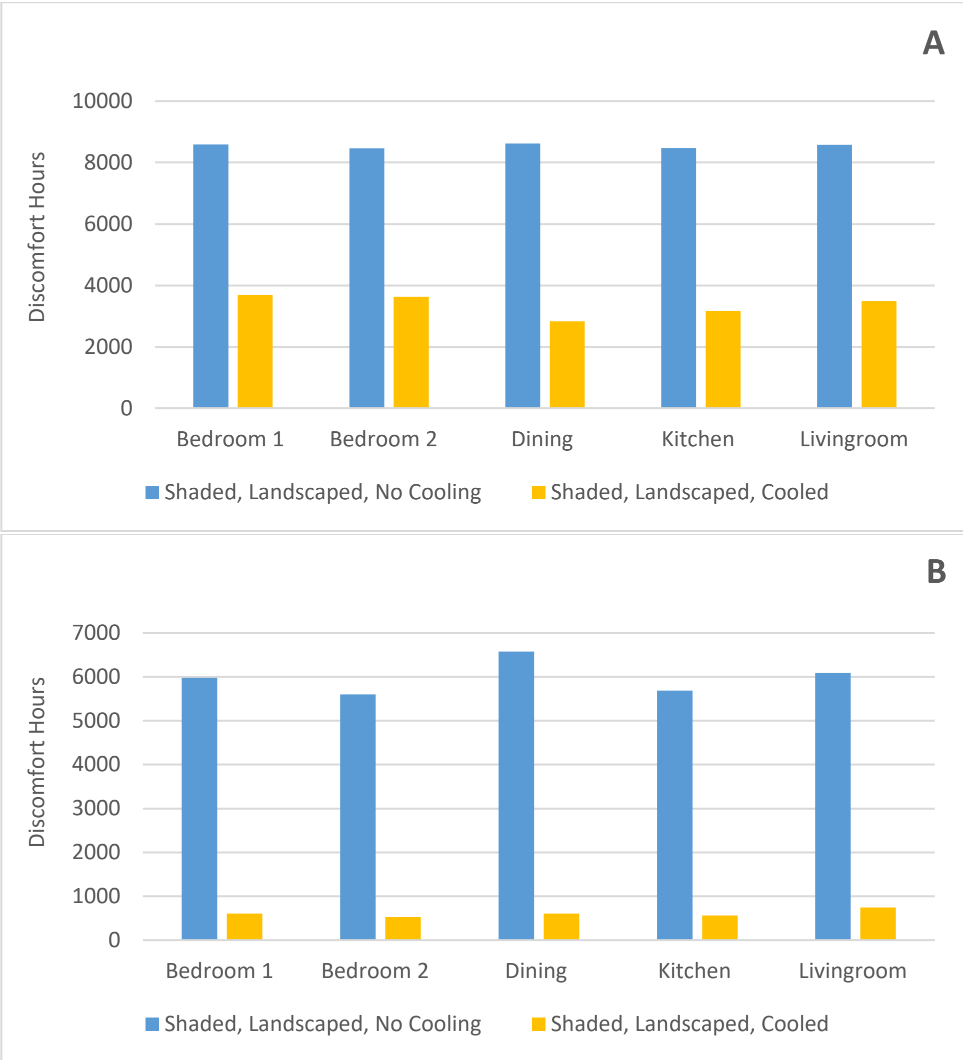

Figure 11 Cooling and landscape impacts on thermal discomfort: (A) Sokoto, (B) Jos

Furthermore, cooling energy demand alone accounts for up to 48% of total energy demand. Jos, despite its current classification as a colder region, exhibited a competing cooling energy demand, compared to the hot climate of Sokoto. This finding supports emerging evidence, including studies by Alegbe and Mtaver (2023), that climate zones such as Bauchi and Jos in Nigeria, traditionally perceived as 'colder' will experience the steepest increase in cooling energy in the future due to shifting climate classifications propelled by extreme warming. Such evolving climatic realities underscore the limitations of historical climate zoning in predicting future performance of buildings. However, in design spaces, as depicted in Figure 12, there were significant differences between observed discomfort hours at the two locations, yielding a percentage variation of between 78.6% (Dining) and 85.6% (Bedroom 2). This challenges conventional design assumptions, and buttresses the exigency of adaptive, future-proofing design approaches tailored to specific regional climate data. Without integrating these future-oriented projections into design frameworks, buildings risk becoming obsolete or thermally dysfunctional over time.

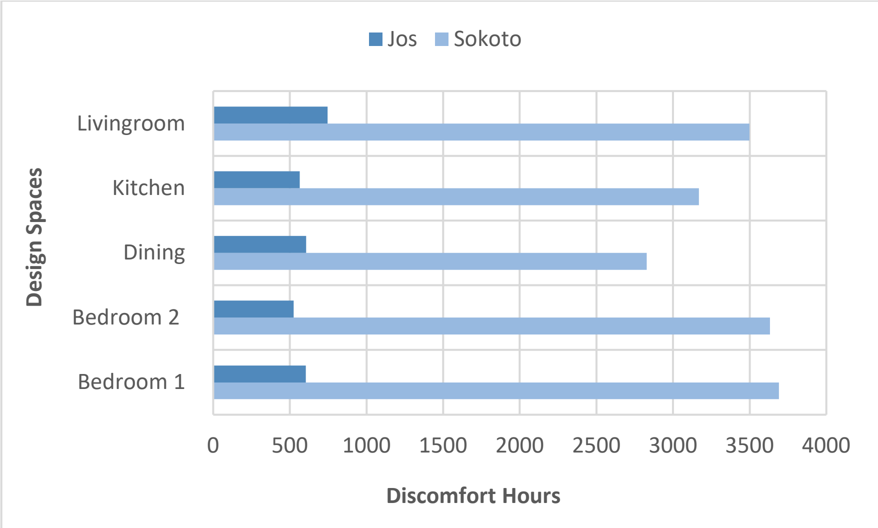

Figure 12 Discomfort hours comparison of landscaped buildings across the locations

6. Conclusion and Recommendations

Conclusion

This study evaluated the influence of landscape features such as trees, lawns and water bodies on the thermal and energy performance of next-generation (Next-G) buildings using a hypothetical residential building in two contrasting Nigerian climates: Sokoto (hot-dry) and Jos (temperate). Dynamic thermal simulations in DesignBuilder were used to assess the variations in impacts across the locations. The study revealed that the inclusion of landscape elements significantly influenced indoor operative temperatures, discomfort hours and energy consumption patterns. In both locations, landscape interventions contributed to a measurable reduction in operative temperatures. Mean annual operative temperature was reduced by up to 2.4% when landscape features were introduced to the building. During the hottest months, peak indoor temperature was reduced by about 2.3%. The effect of landscape on discomfort hours was more pronounced. As observed in the naturally ventilated buildings, discomfort hours reduced by up to 15.8% in Jos.

However, passive landscaping alone was insufficient for attaining the desired indoor comfort range, necessitating the inclusion of mechanical cooling in a mixed-mode setup. With this integrated cooling, discomfort hours significantly reduced by up to 92% in Jos and 68% in Sokoto. These achievements were accompanied by a steep upsurge in energy use per building area, increasing by 48% (118.28 to 228.89 kWh/m²) in Sokoto and by 39% (118.28 to 194.85 kWh/m²) in Jos. In conditioned spaces, the increase was more dramatic, with an observed surge of up to 78% in Sokoto. Moreover, cooling energy alone accounted for 48.3% of total building energy use in Sokoto and approximately 40% in Jos, suggesting that future cooling loads will be substantial, even in regions traditionally considered temperate. This finding challenges the adequacy of relying on passive strategies in tropical contexts, while supporting emerging projections that subtropical zones like Jos will face increased cooling burdens due to climate shifts.

The study confirms that while landscape features can substantially mitigate heat stress and discomfort hours in tropical homes, they cannot independently guarantee indoor comfort under future climate extremes. Consequently, mechanical systems will remain indispensable, but their use must be optimised to avoid excessive energy demand. The integration of landscape and mechanical systems, tailored to local climatic conditions, emerges as an integral pathway for future-proofing Next-G residential buildings in the tropics.

Recommendations

Translating the insights from this study into feasible action requires a multidimensional approach that acknowledges both the technical effectiveness of green landscape features, socio-political and institutional mechanisms to enable their implementation. To ensure future homes in tropical climates, particularly in Nigeria, are truly future-proof, both design practices and policy instruments must evolve in tandem. The recommendations presented below call for a change in basic assumptions about how buildings are conceived, approved and managed in Nigeria's urban and peri-urban contexts, to ensure that the findings of this study can be meaningfully translated into resilient, real-world applications.

I. Integrating Landscape at the Design Stage

A key recommendation is the thoughtful integration of landscape design during the early planning and design stages of building projects. For its effectiveness, it must be upheld as a professional responsibility, enforced by the architect's regulatory body. This measure would ensure that vegetation and green infrastructure are not treated as aesthetic afterthoughts but as integral components of thermal comfort and climate responsiveness. When implemented in unison with building form, orientation and fabric material selection, landscape elements, such as trees, lawns and shrubs can significantly enhance passive cooling and reduce dependence on mechanical systems. To further institutionalise this approach, the submission of a detailed landscape plan should form part of the mandatory building permit application documents. Planning authorities must ensure that projects are evaluated for their ecological performance, while site-level execution must be actively monitored by concerned agencies to ensure that implementation of landscape design does not end on paper.

II. Toward Hybrid Passive-Active Climate Strategies

In the context of the climate crisis, it is no longer enough to rely on passive or active design solutions in isolation. A hybrid approach that combines green landscaping strategies with renewable cooling and ventilation systems is extremely critical. This must be done in a complementary and not competitive manner. For instance, vegetation can be used to shade outdoor spaces to reduce building envelope heat gain during the day, operable windows or ventilated courtyards framed by trees can enable night-time flushing of heat, while energy-efficient systems provide backup during peak thermal discomfort periods. This integrated model should inform future building codes and urban development frameworks.

III. Redefining Climatic Zones and Building Regulations

The current climatic classifications used in Nigeria's planning and building policies are broad and insufficiently nuanced. To guide meaningful low-carbon design responses, a redefinition of climate zones that reflect recent and projected climate realities, including urban heat island effects and microclimate variations across regions, is indispensable. Building regulations should be updated to align with this revised climate classification, with emphasis on green infrastructure, especially in regions where it is most needed. These updated regulations must clearly articulate landscape planning as a performance-based requirement, not merely a decorative element, particularly in housing projects that target low-income and vulnerable populations.

IV. Government Incentives and Local Capacity Building

To support the widespread adoption of these strategies, governments at all levels must provide enabling incentives. These could include subsidised access to ingenious tree species, grants for the installation of water-efficient irrigation systems and reduced development levies for projects that meet defined thermal comfort benchmarks through landscape-based design. To be effective, such incentives must be supported by capacity-building initiatives. Community nurseries and grassroots training programmes should be established to empower residents to plant, maintain and propagate vegetation. Doing so would advance environmental goals, social and economic development by providing green jobs and promoting environmental stewardship at the community level.

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CRediT Authorship Contribution Statement

Mark Alegbe: Conceptualisation, methodology, simulation and results interpretation, writing – original draft preparation. Laurence Chukwuemeka: Supervision, critical review and editing. John Lekwauwa Kalu: Data curation, validation and visualisation. Hammed Nasiru: Literature review and writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing monetary interests or personal relationships that could have influenced the work reported in this paper.

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Data Availability

The data that support the findings of this work are available from the corresponding author upon reasonable request.

Ethics Committee Approval

Approval from an ethics committee was not required for this research.

Resume

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