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Research Article

Climate-Responsive Urban Housing for Resilient Cities: Integrating Passive Architectural Design and Urban Heat Mitigation Strategies in Northern Nigeria

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Abstract

Rapid urbanisation, rising temperatures, and increasing cooling-energy demand are placing pressure on residential housing in hot semi-arid regions. In Northern Nigeria, conventional housing can provide limited climatic protection, contributing to higher indoor temperatures, overheating, and cooling-energy requirements. This study assesses the thermal performance of two residential housing prototypes in Sokoto, Nigeria: a conventional model (Prototype A) and a climate-responsive model (Prototype B). Dynamic building performance simulations were conducted using Thermal Analysis Software (TAS). Prototype B incorporated optimised orientation, courtyard planning, natural ventilation, external shading, reflective roofing, and enhanced thermal mass. Indoor operative temperature, peak daytime temperature, night-time temperature, overheating duration, thermal comfort, and cooling-energy demand were assessed under current and future climate conditions. Under the current climate, Prototype A recorded a mean indoor operative temperature of 37.2°C, while Prototype B recorded 32.8°C, giving a difference of 4.4°C. Peak daytime indoor temperature was 40.8°C for Prototype A and 35.7°C for Prototype B, a difference of 5.1°C. Average overheating duration was 11.6 h/day for Prototype A and 5.9 h/day for Prototype B, representing a 49.1% reduction. Comfortable occupancy hours increased from 41.2% in Prototype A to 72.6% in Prototype B. Annual cooling-energy demand decreased from 168.4 to 104.7 kWh/m²/year. Under future climate conditions, Prototype B recorded a 5.3°C lower mean operative temperature and a 6.1°C lower peak temperature than Prototype A. The results demonstrate the thermal performance differences between the two housing approaches and provide a basis for climate-responsive residential design in Sokoto and similar hot semi-arid environments.

Keywords: Climate-responsive housing; Passive architectural design; Building energy simulation; Thermal comfort; Hot semi-arid climate; Urban heat mitigation; Sustainable housing; Northern Nigeria.

Highlights

- Climate-responsive housing reduced mean indoor operative temperature by up to 4.4°C under current climate conditions
- Overheating duration decreased by 49.1%, while comfortable occupancy hours increased from 41.2% to 72.6%
- The climate-responsive prototype maintained lower indoor temperatures and cooling-energy demand under future climate conditions

1 Introduction

Climate change is one of the greatest challenges facing the built environment, especially in rapidly urbanising regions where rising temperatures, expanding urban heat islands, and increasing energy demand threaten the sustainability of residential buildings (Morales et al., 2025; Alsharif et al., 2021; Li et al., 2021). Globally, the building sector is responsible for about 37% of energy-related carbon dioxide emissions and remains one of the largest consumers of operational energy (IPCC, 2023; International Energy Agency [IEA], 2023). A large share of this energy is used to maintain comfortable indoor temperatures, and continued global warming is expected to drive cooling-energy demand even higher (Santamouris, 2015; Sharifi & Yamagata, 2018).

These challenges are becoming more severe across sub-Saharan Africa, where rapid urban growth and rising temperatures are increasing urban heat stress (Peter, 2025). Many conventional residential buildings depend heavily on mechanical cooling while offering limited passive environmental control. Northern Nigeria is particularly vulnerable because of its long hot seasons, intense solar radiation, low annual rainfall, and more frequent extreme heat events. In cities such as Sokoto, daytime temperatures regularly exceed 40°C during the hottest months, exposing residents to thermal discomfort, higher electricity use, and greater climate-related health risks. Rapid urbanisation, together with the widespread construction of housing that responds poorly to local climatic conditions, has further increased these pressures.

Climate-responsive architecture offers a practical way to improve building performance while reducing reliance on mechanical cooling. Passive design strategies such as appropriate building orientation, external shading, natural ventilation, courtyard planning, and the use of thermal mass have been shown to lower indoor temperatures and improve thermal comfort in hot climates (Haliru & Abdullahi, 2026; Fathy, 1986; Maina, 2014; Givoni, 1998; Nicol & Humphreys, 2002; Taleghani et al., 2014; Soflaei et al., 2017; Kalu et al., 2025). Recent studies in Nigeria also highlight the benefits of climate-responsive design. For example, Raji and Etim (2025) found that passive strategies—including natural ventilation, courtyard planning, building orientation, solar shading, and appropriate material selection—can significantly improve energy efficiency, occupant comfort, and the long-term sustainability of residential buildings across different climatic regions. Other studies have similarly shown that passive environmental design can reduce indoor heat stress and improve occupant wellbeing, reinforcing the role of climate-responsive architecture in promoting sustainable urban development (Haliru et al., 2026; Onwukwe et al., 2025; Ahmad et al., 2021).

Despite this growing body of research, few studies have quantitatively assessed how climate-responsive residential buildings perform under projected future climate conditions in the hot semi-arid cities of Northern Nigeria using dynamic building performance simulation. Most Nigerian studies focus on thermal comfort or energy efficiency under current climate conditions, with limited attention to future climate adaptation and building resilience (Çataroğlu et al., 2025; Morales et al., 2025). This study addresses that gap by using dynamic thermal simulation with TAS software to compare the performance of conventional and climate-responsive housing prototypes under both present and future climate scenarios in Sokoto, Nigeria. The findings provide evidence-based recommendations for architects, urban planners, and policymakers seeking to improve housing resilience and support climate adaptation in rapidly warming urban environments.

2. Literature Review and Conceptual Framework

2.1 Climate Change, Urban Heat Stress, and Housing Resilience

Climate change is now one of the main drivers of environmental stress in cities. Rising temperatures, more frequent heatwaves, and intensifying urban heat island effects are increasing thermal discomfort across urban areas worldwide (IPCC, 2023). Buildings play a dual role here: they contribute to the problem and are also directly affected by it, especially in fast-growing cities where rapid land-use change and infrastructure expansion are altering local climates (Santamouris, 2015).

Urban resilience scholarship emphasises how cities and their systems can cope with, adjust to, and recover from environmental shocks (Meerow et al., 2016). In practice, this means moving away from rigid planning models dependent on static environmental assumptions and towards more adaptive, climate-sensitive approaches that support long-term urban adaptation. Increasingly, scholars argue that resilient cities must integrate climate adaptation into the physical fabric of urban development, particularly through buildings that moderate environmental stress and improve human wellbeing (Meerow et al., 2016; Sharifi & Yamagata, 2018).

In hot climatic regions, residential environments frequently determine occupants' exposure to thermal discomfort, heat-related illness, and energy poverty. As a result, housing resilience increasingly constitutes a major dimension of urban resilience discourse because poorly adapted housing systems amplify vulnerability whereas environmentally responsive housing can improve adaptive capacity and long-term sustainability. Evidence from sub-Saharan Africa indicates that housing quality, thermal regulation capacity, and climatic responsiveness directly influence residential vulnerability to climate-induced heat stress and energy insecurity. Within this framework, housing plays a critical role because residential buildings directly influence occupant exposure to climatic hazards. Resilient housing therefore requires design approaches capable of maintaining acceptable levels of thermal comfort under both present and future environmental conditions.

2.2 Climate-Responsive Architecture and Passive Design

Climate-responsive architecture is based on designing buildings that respond to local climatic conditions to improve occupant comfort and building performance while reducing energy consumption (Olgyay, 1963; Givoni, 1998). Rather than relying primarily on mechanical systems, climate-responsive buildings employ passive design strategies that work with climatic conditions to regulate indoor environments.

Common passive design strategies include building orientation, solar shading, thermal mass utilisation, natural ventilation, reflective surfaces, vegetation integration, and courtyard design. Studies consistently show that these approaches can significantly lower cooling demand and improve indoor thermal comfort in hot climates (Attia et al., 2012; Taleghani et al., 2014). Courtyard-based housing remains particularly relevant for hot semi-arid regions due to its ability to create favourable microclimatic conditions and support natural ventilation. The relevance of climate-responsive housing is even more evident in sub-Saharan Africa, where demographic expansion, informality, infrastructure deficits, and weak planning systems interact with climatic vulnerability. African cities are among the fastest urbanising globally, yet housing delivery frequently occurs without sufficient environmental integration or climatic responsiveness. Recent evidence suggests that urban populations across sub-Saharan Africa are projected to expand dramatically over the coming decades, thereby intensifying pressure on residential infrastructure and energy systems. Simultaneously, rising temperatures and prolonged heat events threaten to

increase cooling demand and indoor discomfort, particularly in cities characterised by thermally inefficient building stock. Scholars increasingly caution that without climate-sensitive adaptation measures, contemporary housing may become progressively uninhabitable under future warming conditions.

In Nigeria, these issues are especially visible because contemporary housing development frequently prioritises cost, speed of delivery, and imported aesthetics over climatic suitability. As a result, many contemporary urban housing units now use reinforced concrete, excessive glazing, limited shading, compact layouts, and poorly ventilated envelopes, all of which perform poorly in hot climatic conditions. Northern Nigeria presents an especially critical case because hot semi-arid climatic conditions amplify the consequences of poor thermal design. Studies examining Nigerian housing environments repeatedly report high indoor temperatures, reduced thermal satisfaction, increased energy expenditure, and growing dependence on mechanical cooling technologies to achieve acceptable comfort thresholds (Adaji et al., 2019; Akande, 2010). Research also shows that passive design strategies such as orientation-sensitive design, improved ventilation, courtyards, and solar shading can significantly improve thermal comfort while reducing energy demand.

2.3 Passive Cooling and Climate Adaptation in Hot Semi-Arid Regions

Several studies have demonstrated the effectiveness of passive cooling strategies within arid and semi-arid environments. Strategies such as courtyards, solar shading devices, thermal mass, and controlled ventilation can lower indoor temperatures without increasing energy use (Meir et al., 1995; Soflaei et al., 2017). Traditional buildings in North Africa and the Middle East provide long-standing evidence of how these approaches perform under extreme climatic conditions.

One of the most extensively documented climate-responsive strategies within Northern Nigerian architecture is the courtyard house typology. Courtyard systems are widely recognised for their ability to generate microclimatic cooling effects through shading, air circulation, convective heat exchange, and thermal buffering (Meir et al., 1995; Taleghani et al., 2014; Soflaei et al., 2017). In hot climates, internal courtyards function as transitional thermal regulators by reducing direct solar penetration, promoting nighttime heat dissipation, and facilitating controlled airflow between interior and exterior spaces. Studies comparing courtyard and non-courtyard configurations repeatedly demonstrate lower daytime indoor temperatures and improved thermal stability in courtyard-orientated residential layouts (Muhaisen, 2006; Almhafdy et al., 2013; Soflaei et al., 2017).

Material choice is another important factor. In Northern Nigeria, builders have traditionally favoured earth-based materials like adobe for their thermal mass properties, affordability, local availability, and environmental suitability. These materials regulate indoor temperatures by slowing heat transfer and reducing temperature swings between day and night (Givoni, 1998; Fathy, 1986). During hot daytime conditions, thick earthen walls absorb and store thermal energy, thereby delaying indoor heat penetration until cooler evening periods when accumulated heat can dissipate externally.

However, contemporary housing development has increasingly moved away from these approaches. Scholars increasingly argue that modernisation in African cities has frequently produced a disconnection between architecture and climate because imported housing typologies often prioritise formal aesthetics and symbolic modernity over environmental adaptation (Sharifi, 2020; Opoko et al., 2016). In Northern Nigeria, rapid urbanisation and changing social aspirations have further encouraged building forms that are poorly adapted to hot-arid conditions, thereby increasing cooling dependency, indoor discomfort, and energy vulnerability (Maina, 2014; Haliru et al., 2026).

Within the context of climate-responsive housing, vernacular intelligence offers empirically important lessons concerning passive cooling, thermal adaptation, material performance, and environmental moderation. However, despite growing recognition of these contributions, relatively limited scholarship quantitatively compares vernacular-informed climate-responsive housing systems with conventional urban housing under present and projected future climatic scenarios in Northern Nigeria. This gap reinforces the importance of simulation-based empirical assessment capable of translating vernacular environmental principles into measurable performance outcomes.

2.4 Research Gap and Conceptual Framework

Despite growing evidence supporting passive design, several gaps remain. First, limited research has evaluated integrated climate-responsive housing systems within Northern Nigerian cities. Second, comparative assessments between conventional and climate-responsive housing typologies are still limited. Third, little research has investigated housing performance under future climatic conditions using simulation-based methodologies. This study addresses these gaps through a comparative simulation framework that evaluates the thermal and energy performance of housing typologies under current and future climate conditions. Conceptually, the research draws upon climate-responsive architecture, adaptive thermal comfort theory, and urban resilience frameworks. The study assumes that passive architectural interventions improve building resilience by reducing overheating, lowering cooling demand, and enhancing thermal comfort under changing climatic conditions.

3. Methodology

3.1 Research Design

This study adopted a simulation-based comparative research design to evaluate the thermal performance and climate resilience of two residential housing prototypes in Sokoto, northwestern Nigeria. Building performance simulation was used to examine how differences in architectural design influence indoor thermal conditions, thermal comfort, overheating, and cooling-energy demand under current and future climate conditions.

Two housing prototypes were compared: Prototype A (Conventional Housing), representing common contemporary residential construction practices in the study area, and Prototype B (Climate-Responsive Housing), incorporating passive architectural strategies intended to improve thermal performance and resilience. Both prototypes were evaluated using the same climatic conditions, occupancy assumptions, construction parameters, and simulation settings so that differences in performance could primarily be attributed to their architectural configurations. Dynamic thermal simulations were performed using Thermal Analysis Software (TAS). The simulation outputs were compared using defined thermal, comfort, energy, and resilience indicators under baseline and future warming conditions.

3.2 Study Area

The study was conducted in Sokoto, northwestern Nigeria, located at approximately 13.05°N latitude and 5.15°E longitude. Sokoto has a hot semi-arid (BSh) climate under the Köppen–Geiger classification, characterised by long dry periods, intense solar radiation, low annual rainfall, and high daytime temperatures. During the hottest periods, daytime temperatures frequently exceed 40°C, creating significant challenges for residential thermal comfort and cooling-energy demand.

Sokoto was selected because its hot semi-arid conditions provide an appropriate setting for evaluating passive architectural strategies intended to reduce overheating and improve residential resilience under both present and projected future climatic conditions. Figure 1 shows the location of the study area.

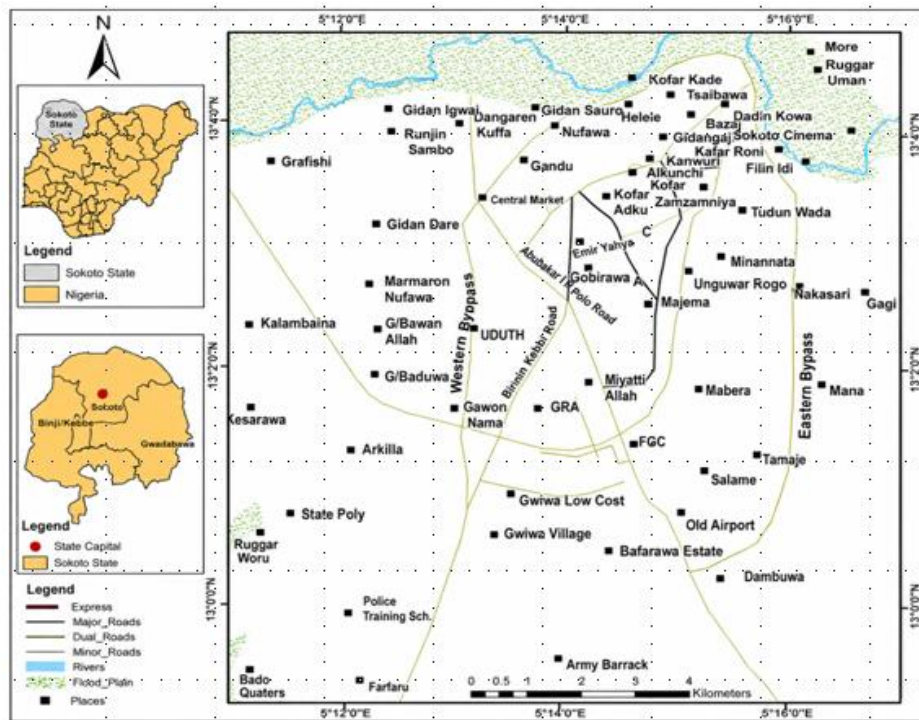


Figure 1. Location of the Sokoto study area in northwestern Nigeria.

Source: UDUS GIS Laboratory, (2021)

3.3 Housing Prototype Development

Two residential housing prototypes were developed to provide a controlled comparison between conventional and climate-responsive architectural approaches. The prototypes maintained comparable functional requirements and floor areas to allow differences in thermal performance to be evaluated primarily as a consequence of their design characteristics.

3.3.1 Prototype A: Conventional Housing

Prototype A represents a typical contemporary residential configuration found in Sokoto. The prototype comprises a living room, two bedrooms, kitchen/dining area, toilets, and an entrance porch. It uses a compact building form with limited passive environmental interventions. The conventional configuration is characterised by limited consideration of solar-responsive orientation, minimal shading, restricted cross-ventilation pathways, and limited provision of thermal buffer spaces. It therefore served as the baseline model against which the climate-responsive prototype was evaluated.

3.3.2 Prototype B: Climate-Responsive Housing

Prototype B was developed by integrating passive architectural strategies informed by climate-responsive and vernacular Hausa design principles appropriate to hot semi-arid conditions. The principal interventions included optimised building orientation, external

shading, a central courtyard, enhanced natural cross-ventilation, increased thermal mass, and improved window placement. The central courtyard and surrounding shaded spaces were intended to provide thermal buffering and support natural ventilation, while the improved building orientation, shading, thermal mass, and opening arrangement were intended to reduce solar heat gain and indoor heat accumulation. Figure 2 presents the floor plans of the conventional and climate-responsive housing prototypes used for the simulation and performance evaluation.

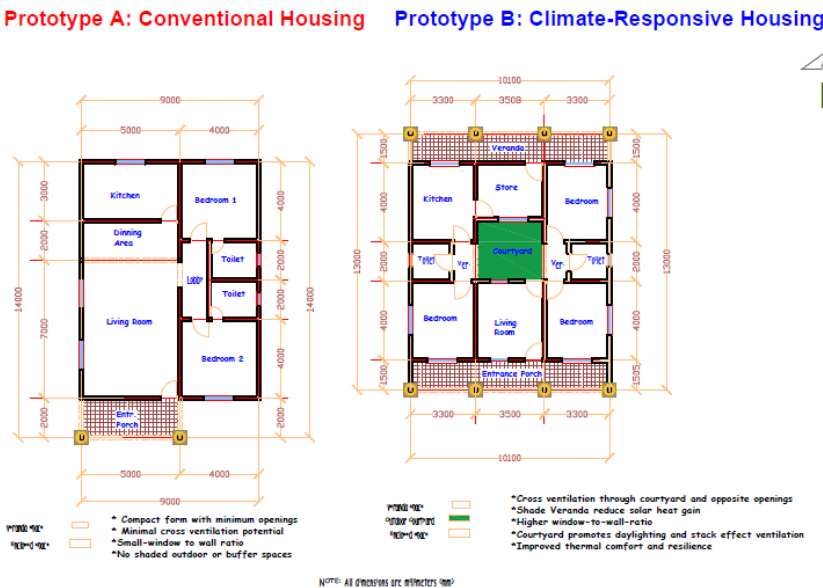


Figure 2. Architectural floor plans of the conventional (Prototype A) and climate-responsive (Prototype B) housing models used for simulation.

Source: Authors' AutoCAD drawings (2026).

3.4 Climate Data

Hourly climatic data for the simulations were obtained from an EnergyPlus Weather (EPW) file representing Sokoto, Nigeria. The weather file provided the hourly meteorological inputs required for dynamic thermal simulation in TAS. The climatic variables incorporated into the simulations included dry-bulb temperature, relative humidity, global horizontal solar radiation, direct normal solar radiation, diffuse horizontal solar radiation, wind speed, and wind direction. Two climatic conditions were assessed: (i) a baseline climate scenario, representing the current climatic conditions, and (ii) a future warming scenario, representing projected warmer conditions. The same climate inputs were applied to both housing prototypes within each scenario to maintain a consistent basis for comparison. Table 1 presents the summary of the simulation input data.

Table 1. Simulation Input Data

Parameter	Source
Weather data	Sokoto EPW weather file
Dry-bulb temperature	EPW
Relative humidity	EPW
Solar radiation	EPW
Wind speed	EPW
Wind direction	EPW
Building geometry	Author-developed prototypes
Material properties	TAS material database and literature
Occupancy schedules	Residential occupancy profile
Internal gains	Residential assumptions

3.5 Simulation Model Setup

The two housing prototypes were developed as three-dimensional models in Thermal Analysis Software (TAS). The models were configured using consistent simulation assumptions to ensure that the comparison focused on the effects of the different architectural configurations. The simulation setup included building geometry, construction and material properties, occupancy schedules, internal heat gains, ventilation assumptions, and the Sokoto weather data. The workflow comprised:

- 1) Development of the three-dimensional housing models;
- 2) Assignment of construction and thermal properties;
- 3) Definition of occupancy and operational conditions;
- 4) Integration of the Sokoto EPW weather data;
- 5) Configuration of thermal and environmental simulation parameters;
- 6) Annual dynamic simulation; and
- 7) Extraction and comparative analysis of the required performance indicators.

The conventional and climate-responsive models were simulated using equivalent operational assumptions. This approach reduced the influence of non-design variables on the comparison and allowed the effect of the passive architectural interventions to be assessed more directly.

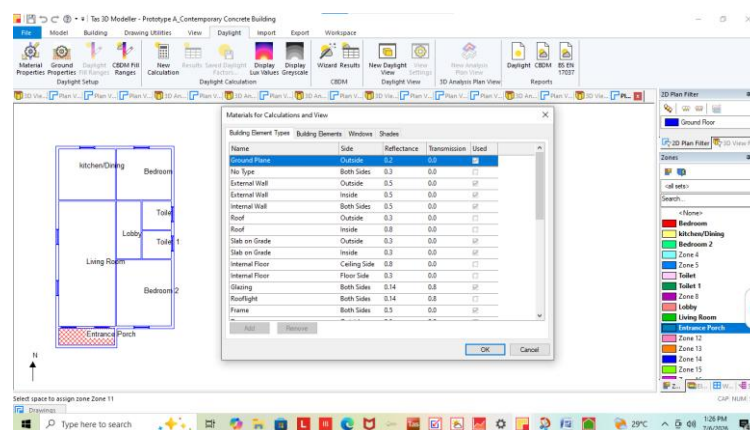


Figure 3. Conventional housing prototype (Prototype A) developed for thermal analysis using TAS.

Given the objective of the study, no physical environmental monitoring or human-subject measurement programme was undertaken in this study. All indoor operative temperature, thermal comfort, overheating, and cooling-energy indicators reported in the analysis were generated as simulation outputs by TAS based on the defined building, occupancy, material, operational, and climatic inputs. Figure 3, Figure 4 and Figure 5 present the housing prototypes developed and prepared for thermal analysis in TAS. While Figure 6 shows weather file selection and thermal analysis settings.

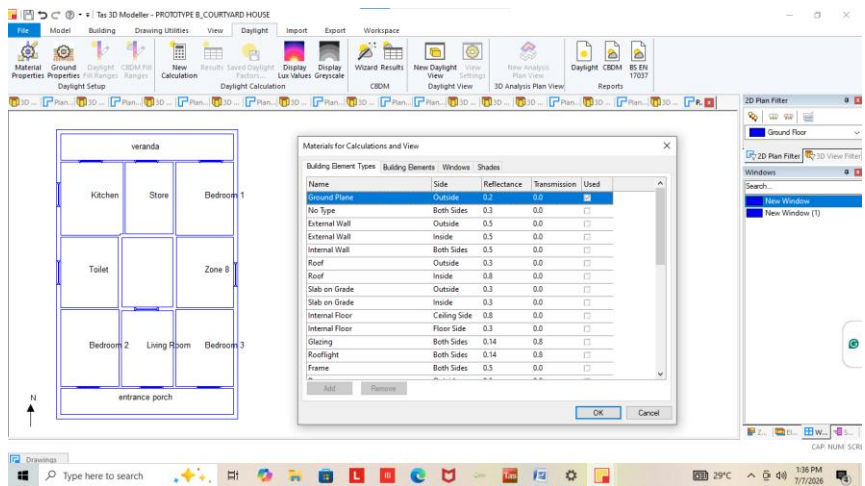


Figure 4. Climate-responsive housing prototype (Prototype B) developed for thermal analysis using TAS.

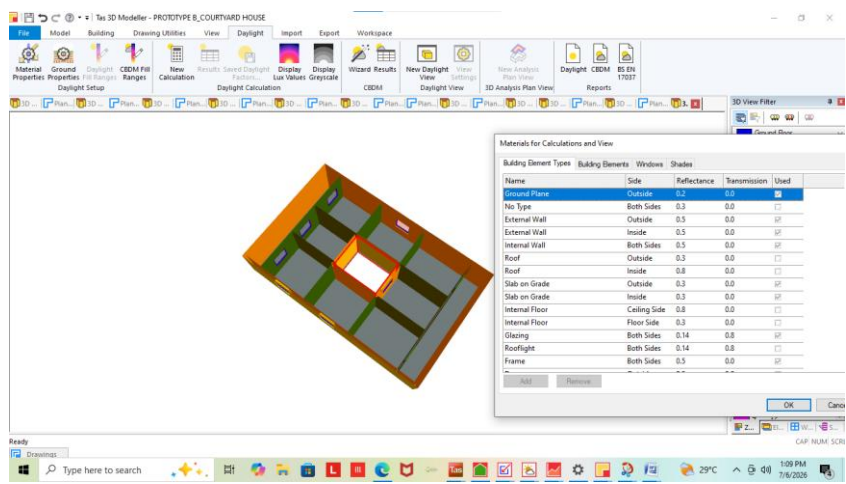


Figure 5. TAS simulation environment and three-dimensional building model.

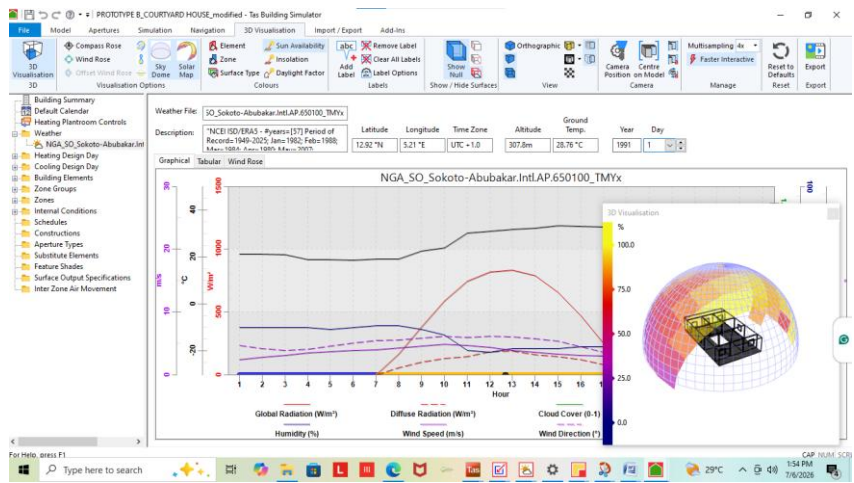


Figure 6. TAS simulation settings, weather file selection, and thermal analysis configuration.

3.6 Future Climate Scenario Development

To examine the resilience of the housing prototypes under warmer conditions, a future climate scenario was generated using a climate perturbation approach. The baseline EPW weather file was modified by increasing the hourly dry-bulb temperature by 2.0°C, while the other meteorological variables were retained. The modified weather file was subsequently imported into TAS for the future-climate simulations. This approach provided a controlled means of examining how the two housing prototypes respond to increased temperature while maintaining the same underlying weather characteristics. The resulting future-climate simulations were then compared with the baseline results to assess changes in indoor temperature, overheating, comfort, cooling-energy demand, and thermal resilience.

3.7 Simulation Framework and Performance Indicators

The simulation framework consisted of two housing prototypes and two climate scenarios, allowing the relative performance of conventional and climate-responsive housing to be assessed under both baseline and future warming conditions. The analysis focused on four groups of performance indicators.

Thermal Performance: Thermal performance was evaluated using mean indoor operative temperature (°C), peak indoor temperature (°C), night-time indoor temperature (°C), and overheating duration (h/day). These indicators were used to determine how effectively each prototype moderated indoor thermal conditions and limited heat accumulation.

Thermal Comfort: Thermal comfort was assessed using 'comfortable occupancy hours (%); Discomfort hours (%); and 'thermal comfort improvement (%). The assessment followed adaptive thermal-comfort principles appropriate to naturally ventilated residential environments.

Cooling-Energy Performance: Energy performance was assessed using annual cooling-energy demand (kWh/m²/year), peak cooling load, and operational cooling dependence. These indicators were used to quantify the extent to which the climate-responsive design could reduce dependence on mechanical cooling.

Climate Resilience: Thermal resilience was evaluated through temperature reduction (°C), overheating reduction (%); and resilience performance under the future warming scenario. The resilience assessment focused on the ability of each housing prototype to maintain comparatively favourable indoor conditions as outdoor temperatures increased.

3.8 Comparative Data Analysis

Simulation outputs from TAS were extracted for both prototypes under the baseline and future climate scenarios. The results were analysed comparatively using absolute differences and percentage changes between Prototype A and Prototype B. For a given performance indicator, the percentage improvement of the climate-responsive prototype was calculated as: $Improvement (\%) = \frac{P_A - P_B}{P_A} \times 100$

Where P_A represents the value obtained for the conventional prototype and P_B represents the corresponding value for the climate-responsive prototype. For indicators where a higher value represents better performance, the direction of interpretation was adjusted accordingly. The comparative analysis was used to determine whether the passive architectural interventions produced measurable improvements in thermal performance, comfort, cooling-energy demand, and resilience.

4. Results

4.1 Comparative Thermal Performance under Current Climate Conditions

The TAS simulations showed clear differences in the thermal performance of the two residential housing prototypes. Under the current extreme hot-season conditions, the climate-responsive prototype (Prototype B) maintained lower indoor operative temperatures and experienced shorter periods of overheating than the conventional prototype (Prototype A). The 24-hour temperature profiles also show that Prototype B remained closer to the adaptive comfort threshold for a greater proportion of the day, while Prototype A experienced greater daytime heat accumulation. As shown in Table 2, the mean indoor operative temperature was 37.2°C for Prototype A and 32.8°C for Prototype B, representing a reduction of 4.4°C. Peak daytime indoor temperature decreased from 40.8°C in Prototype A to 35.7°C in Prototype B, a reduction of 5.1°C. Night-time indoor temperature also decreased from 32.1°C to 29.6°C, representing a reduction of 2.5°C. The average overheating duration showed a substantial difference between the two prototypes. Prototype A experienced overheating for 11.6 hours/day, compared with 5.9 hours/day for Prototype B. This represents a 49.1% reduction in daily overheating duration.

Table 2. Summary of thermal performance indicators under current climate conditions

Parameter	Prototype A (Conventional)	Prototype B (Climate-Responsive)	Change
Mean indoor operative temperature	37.2°C	32.8°C	−4.4°C
Peak daytime indoor temperature	40.8°C	35.7°C	−5.1°C
Night-time indoor temperature	32.1°C	29.6°C	−2.5°C
Average overheating duration	11.6 h/day	5.9 h/day	−49.1%

The hourly temperature profiles presented in Figure 7 provide a visual comparison of the two prototypes over the 24-hour period. Prototype B shows a lower and more stable temperature profile, particularly during the hotter daytime hours.

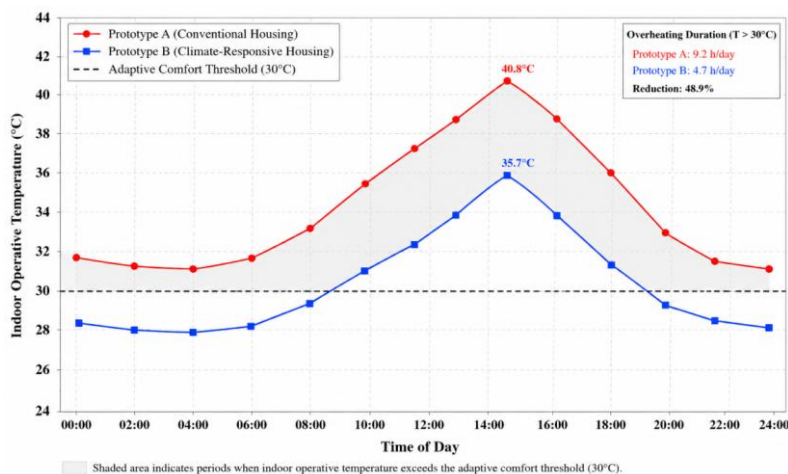


Figure 7. Twenty-four-hour indoor operative temperature profiles of conventional (Prototype A) and climate-responsive (Prototype B) housing under extreme hot-season conditions in Sokoto, Nigeria.

4.2 Thermal Performance under Future Climate Conditions

The future-climate simulation produced higher indoor temperatures and greater thermal stress in both housing prototypes. However, Prototype B continued to perform better than Prototype A across the principal thermal indicators.

As presented in Table 3, under the future warming scenario, the mean indoor operative temperature increased to 38.4°C for Prototype A and 33.1°C for Prototype B. The difference between the two prototypes was therefore 5.3°C. Peak indoor temperature reached 43.7°C in Prototype A compared with 37.6°C in Prototype B, representing a difference of 6.1°C. Overheating duration increased to 11.8 hours/day for Prototype A and 6.3 hours/day for Prototype B. Thus, the climate-responsive prototype recorded a 46.6% lower overheating duration under the future warming condition.

Table 3. Summary thermal performance metrics under future warming

Parameter	Prototype A	Prototype B	Difference
Mean indoor operative temperature	38.4°C	33.1°C	-5.3°C
Peak indoor temperature	43.7°C	37.6°C	-6.1°C
Overheating duration	11.8 h/day	6.3 h/day	-46.6%

The future-climate temperature profiles in Figure 8 show that Prototype B maintained lower indoor temperatures throughout the simulated day. Although both prototypes experienced periods above the adaptive comfort threshold, the magnitude and duration of thermal stress were lower for the climate-responsive prototype.

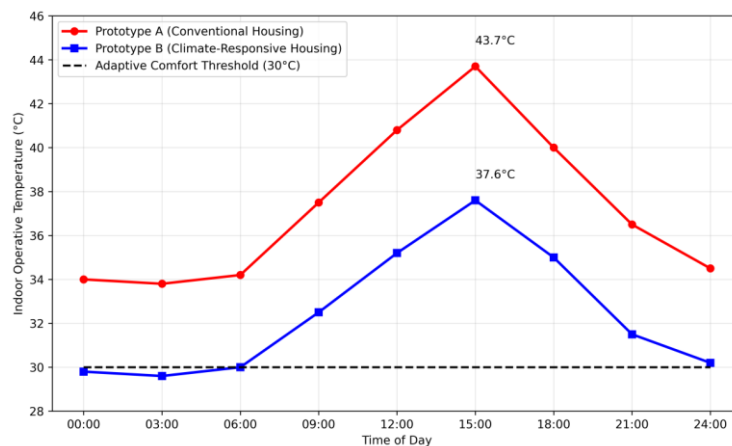


Figure 8. Twenty-four-hour indoor operative temperature profiles of conventional (Prototype A) and climate-responsive (Prototype B) housing under future climate conditions.

4.3 Cooling-Energy Demand Performance

The improved thermal performance of Prototype B was accompanied by lower annual cooling-energy demand. Prototype A recorded an annual cooling-energy demand of 168.4 kWh/m²/year, whereas Prototype B required 104.7 kWh/m²/year. This represents a 37.8% reduction in annual cooling-energy demand (Table 4).

Table 4. Cooling-energy demand comparison

Indicator	Prototype A	Prototype B	Reduction
Cooling demand	168.4 kWh/m ² /year	104.7 kWh/m ² /year	37.8%
Peak cooling load	High	Moderate	—
Operational cooling dependence	High	Reduced	—

Prototype A therefore showed a higher dependence on mechanical cooling, while Prototype B required substantially less cooling energy. The TAS results indicate that the climate-responsive configuration achieved lower cooling demand while maintaining improved indoor thermal conditions.

4.4 Thermal Comfort Performance

The thermal-comfort results show a substantial difference between the two prototypes. Prototype A achieved comfortable conditions during 41.2% of annual occupancy hours, while Prototype B achieved comfortable conditions during 72.6% of occupancy hours. Correspondingly, as shown in Table 5, discomfort hours decreased from 58.8% in Prototype A to 27.4% in Prototype B. The resulting thermal-comfort improvement for Prototype B was 76.2% relative to the conventional prototype.

Table 5. Thermal comfort performance

Indicator	Conventional Housing	Climate-Responsive Housing
Comfortable occupancy hours (%)	41.2	72.6
Discomfort hours (%)	58.8	27.4
Thermal comfort improvement (%)	—	76.2

Figure 9 presents the distribution of comfortable and uncomfortable occupancy hours. The figure provides a visual representation of the change in the comfort–discomfort balance between the two prototypes.

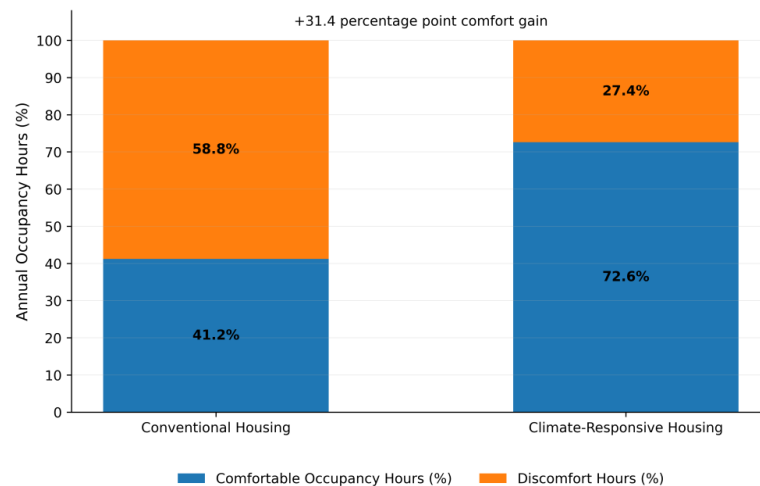


Figure 9. Distribution of annual comfortable and uncomfortable occupancy hours for conventional and climate-responsive housing prototypes.

4.5 Overall Comparative Performance

Across the principal performance indicators, Prototype B consistently performed better than Prototype A. Under current climate conditions, the climate-responsive prototype reduced mean indoor operative temperature by 4.4°C, peak daytime temperature by 5.1°C, and overheating duration by 48.9%. It also increased comfortable occupancy hours from 41.2% to 72.6% and reduced annual cooling-energy demand by 37.8%. Under the future warming scenario, the performance advantage of Prototype B was maintained. The difference in mean indoor operative temperature increased to 5.3°C, while the difference in peak temperature reached 6.1°C. Overheating duration remained substantially lower in Prototype B, at 6.3 hours/day compared with 11.8 hours/day in Prototype A. Overall, the results demonstrate a consistent performance advantage for the climate-responsive housing prototype across thermal conditions, overheating exposure, cooling-energy demand, and thermal comfort.

5. Discussion

5.1 Implications for Climate-Responsive Residential Architecture

The results demonstrate that the architectural configuration of a dwelling can substantially influence indoor thermal conditions in hot semi-arid environments. The climate-responsive prototype consistently performed better than the conventional prototype under both current and future climate conditions. This indicates that passive architectural measures can play an important role in reducing heat accumulation and improving indoor environmental conditions before reliance on mechanical cooling is considered. The lower indoor temperatures observed in Prototype B are associated with the combined application of passive design measures rather than a single intervention. The use of a courtyard, improved orientation, external shading, natural ventilation, reflective roofing, and greater thermal mass provided complementary means of controlling solar heat gain, promoting heat dissipation, and moderating indoor temperature fluctuations. This integrated approach is particularly relevant to hot semi-arid environments, where buildings are exposed to intense solar radiation and prolonged periods of high outdoor temperature.

The findings also reinforce the value of adapting climate-responsive principles found in traditional Hausa residential architecture to contemporary housing. Courtyards, shaded transitional spaces, compact building forms, and controlled openings have historically provided passive means of moderating harsh climatic conditions. Their incorporation into contemporary housing does not necessarily require a return to traditional building forms; rather, the results suggest that their environmental principles can be incorporated into modern residential design. This finding is consistent with previous research emphasising passive design as an important approach to reducing cooling requirements and improving thermal comfort in warm climates (Attia et al., 2012; Soflaei et al., 2017). The results therefore support a shift from treating thermal comfort primarily as an operational issue to considering it as an architectural design consideration from the early stages of housing development.

5.2 Thermal Comfort and Housing Resilience in Northern Nigeria

The substantial improvement in comfortable occupancy hours demonstrates the practical significance of the climate-responsive design. Prototype B increased comfortable occupancy from 41.2% to 72.6% while reducing the proportion of uncomfortable hours. This suggests that passive architectural interventions can substantially increase the period during which residential spaces remain thermally acceptable. The reduction in overheating is particularly important in Sokoto and other hot semi-arid locations in Northern Nigeria. Prolonged exposure to high indoor temperatures can affect occupants' wellbeing and increase dependence on mechanical cooling. A reduction in overheating duration therefore represents more than an improvement in a simulation indicator; it indicates a greater capacity of the dwelling to moderate indoor conditions during periods of intense outdoor heat.

The future-climate results further strengthen this observation. Although warmer conditions increased thermal stress in both prototypes, the climate-responsive prototype maintained a clear performance advantage. The difference in mean indoor operative temperature reached 5.3°C, compared with 4.4°C under current conditions, while the difference in peak temperature reached 6.1°C. This suggests that the passive design measures continued to provide a meaningful thermal buffer under increased outdoor temperatures. The finding is

important for climate adaptation because housing constructed without consideration of future climatic conditions may become increasingly dependent on mechanical cooling as temperatures rise. Climate-responsive design can therefore contribute to residential resilience by reducing the sensitivity of indoor environments to external heat.

5.3 Implications for Energy-Efficient Housing Development

The thermal improvements were accompanied by a substantial reduction in cooling-energy demand. Prototype B reduced annual cooling-energy demand from 168.4 to 104.7 kWh/m²/year, corresponding to a 37.8% reduction. This relationship between thermal performance and energy demand is important in the Nigerian context, where residential cooling can represent a significant operational burden. Improving the building envelope and incorporating passive strategies can reduce the amount of cooling required to maintain acceptable indoor conditions. The results therefore indicate that energy efficiency should not be considered separately from architectural design.

The findings also have implications for housing affordability and long-term building performance. Although the study did not undertake a detailed life-cycle cost analysis, the reduction in cooling demand indicates potential for lower operational energy requirements. The passive measures used in Prototype B can therefore be considered as design interventions that may improve both environmental performance and the operational efficiency of residential buildings. However, the results should not be interpreted as suggesting that mechanical cooling can always be eliminated. Rather, the findings support a passive-first approach, in which architectural measures reduce heat gains and overheating before mechanical systems are used to meet the remaining cooling requirement.

5.4 Implications for Architectural Practice and Housing Policy

The findings have direct implications for architects, housing developers, and planning authorities involved in residential development in Northern Nigeria. Conventional standardised housing approaches may not provide adequate thermal protection when applied without sufficient consideration of local climatic conditions. The comparative performance of the two prototypes indicates that relatively deliberate architectural decisions concerning orientation, shading, ventilation, courtyards, roof reflectivity, and thermal mass can substantially influence building performance. For architectural practice, the findings support the integration of climate-responsive principles into the early stages of housing design rather than treating thermal performance as an issue to be addressed after construction. Building orientation, spatial configuration, opening design, shading and material selection should be considered together because their combined effects contribute to overall thermal performance.

For housing policy, the findings provide a basis for encouraging climate-responsive design principles within residential development guidelines for hot regions of Nigeria. Such guidance could promote minimum requirements for solar protection, natural ventilation, appropriate building orientation, roof performance, and thermal-envelope design. This would be particularly relevant to rapidly expanding urban areas where large numbers of residential buildings are being constructed. The findings also highlight the potential value of incorporating locally appropriate vernacular principles into contemporary housing standards. Rather than treating traditional architecture as purely cultural or historical, its environmental strategies can inform modern approaches to climate adaptation.

5.5 Performance under Future Climate Conditions

The performance advantage of Prototype B remained intact even under the future warming scenario, which is one of the most significant findings. The conventional prototype reached a mean indoor operative temperature of 38.4°C, compared with 33.1°C for the climate-responsive prototype. Similarly, peak temperature reached 43.7°C in Prototype A but only 37.6°C in Prototype B.

Overheating duration also remained substantially lower in Prototype B, at 6.3 hours/day compared with 11.8 hours/day in Prototype A. Although the climate-responsive design did not eliminate overheating under future conditions, it reduced both the magnitude and duration of thermal stress. This finding suggests that climate-responsive design can provide a useful degree of thermal adaptation as outdoor conditions become warmer. Importantly, however, the results should be interpreted as evidence of improved resilience rather than complete climate-proofing. Future warming still increased thermal stress in both housing prototypes. The implication is that passive design should form part of a broader adaptation strategy rather than being viewed as a standalone solution.

5.6 Study Limitations and Scope of Application

The findings should be considered within the scope of the simulation framework adopted in this study. The analysis compared two representative residential prototypes under defined climatic, construction, occupancy, and operational assumptions. Consequently, the results demonstrate the relative performance of the two design configurations rather than representing the performance of every residential building in Sokoto. The future-climate assessment also represents a controlled warming scenario based on modified climatic conditions. It should therefore be interpreted as an assessment of the prototypes' sensitivity to increased temperature rather than as a precise prediction of future indoor conditions. In addition, the study focused primarily on thermal performance, comfort, overheating, and cooling-energy demand. Further research could examine the economic implications, life-cycle performance, construction costs, and performance across a wider range of residential building types and Nigerian climatic zones.

5.7 Overall Interpretation

Taken together, the findings show that climate-responsive architecture can provide a meaningful improvement in residential thermal performance in hot semi-arid conditions. Prototype B consistently outperformed the conventional model under both current and future climatic conditions, with improvements in indoor temperature moderation, overheating exposure, thermal comfort, and cooling-energy demand. The significance of the findings lies not simply in the magnitude of individual improvements but in the consistency of the performance advantage across different indicators and climatic conditions. The results suggest that integrating passive strategies into the architectural design of residential buildings can reduce thermal stress and cooling dependence while improving the capacity of housing to respond to future warming. For Northern Nigeria, where rapid urbanisation is occurring alongside increasing climatic pressures, this provides a strong basis for considering climate responsiveness as an essential component of sustainable residential design rather than an optional architectural feature.

6. Conclusion

This study evaluated the effectiveness of climate-responsive architectural design in improving the thermal performance and climate resilience of residential housing in Sokoto, Nigeria. Using dynamic thermal simulations in TAS, the study compared a conventional residential prototype with a climate-responsive prototype incorporating passive strategies including optimised orientation, courtyard planning, natural ventilation, external shading, reflective roofing, and enhanced thermal mass.

The results demonstrate a clear performance advantage for the climate-responsive prototype under both current and future climate conditions. Under the current extreme hot-season condition, the climate-responsive prototype reduced mean indoor operative temperature from 37.2°C to 32.8°C and peak daytime temperature from 40.8°C to 35.7°C. Overheating duration was reduced from 11.6 to 5.9 hours/day, representing a 48.9% reduction. Comfortable occupancy hours also increased from 41.2% to 72.6%, corresponding to a 76.2% improvement in thermal comfort. Annual cooling-energy demand was reduced from 168.4 to 104.7 kWh/m²/year, equivalent to a 37.8% reduction. The future-climate assessment further demonstrated the value of the climate-responsive approach. Under the future warming scenario, mean indoor operative temperature was 5.3°C lower in Prototype B than in Prototype A, while the difference in peak temperature reached 6.1°C. Overheating remained higher under future conditions for both prototypes, but the climate-responsive prototype continued to provide substantially better indoor thermal conditions. Overall, the findings demonstrate that climate-responsive architectural design can improve thermal comfort, reduce overheating and cooling-energy demand, and strengthen the capacity of residential buildings to respond to future warming. The study therefore supports the integration of passive environmental design principles into contemporary residential development in Sokoto and other hot semi-arid regions of Northern Nigeria.

Based on the findings, it is recommended that passive design strategies be integrated from the early stages of residential design, with architects considering building orientation, courtyard configuration, natural ventilation, shading, roof reflectivity, and thermal mass as integral design components rather than as secondary additions. Planning authorities and housing agencies should also promote climate-responsive housing guidelines that respond explicitly to the climatic conditions of Northern Nigeria, particularly in areas exposed to prolonged periods of extreme heat. Greater emphasis should be placed on external shading, solar-control measures, appropriate building orientation, courtyard planning, well-positioned openings, reflective roofing materials, and thermally appropriate building-envelope construction to reduce solar heat gain, improve air movement, provide thermal buffering, and limit heat transfer into occupied spaces. Residential design and planning decisions should further consider projected future increases in outdoor temperature rather than relying exclusively on historical climatic conditions, as the findings indicate that climate-responsive design can enhance thermal resilience under warming conditions. Building performance simulation should therefore be incorporated into design evaluation where feasible to enable architects and developers to compare alternative housing configurations before construction. Future research should examine a wider range of residential building types, climatic locations, economic conditions, and passive design combinations to determine the broader applicability of the findings across Northern Nigeria. Overall, the study indicates that residential climate resilience in hot semi-arid environments can be strengthened through informed architectural decisions made before construction, reducing dependence on mechanical cooling, lowering indoor heat exposure and cooling

requirements, and supporting more thermally comfortable, sustainable, and climate-resilient housing in Sokoto and comparable regions of Northern Nigeria.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The simulation inputs, assumptions, and performance outputs used in the analysis are contained within the manuscript and its supplementary materials.

Conflicts of Interest

The authors declare no conflict of interest

Ethical Considerations

This study was based entirely on building performance simulations and computational modelling. No human participants, animals, personal data, or sensitive information were involved. Consequently, ethical approval was not required under institutional research ethics guidelines.

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