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INTEGRATING BIOPHILIC DESIGN AND SMART TECHNOLOGIES FOR URBAN HEAT ISLAND MITIGATION IN RESIDENTIAL COMMUNITIES OF SOUTHEAST NIGERIA

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Abstract

Abstract: The intensification of the urban heat island (UHI) effect across residential communities in Southeast Nigeria has continued to result in the deterioration of environmental quality and increasing demand for cooling energy. Such effect, as triggered by anthropogenic heat emissions, increasing surface areas of imperviousness, loss of greenery, and rapid urbanisation, also causes thermal discomfort. Although existing studies have identified the limitless capabilities of biophilic design principles (BDP) and smart technologies (ST), a significant gap persists in how to evolve and deploy an integrated climate-responsive intervention that is bespoke to tropical residential environments. To this end, this study critically investigated the integration of a BDP/ST intervention for the mitigation of UHI in residential communities of Aba, Awka, Abakiliki, Enugu, and Owerri. With the implementation of a convergent parallel mixed method design, fifteen residential communities, representing low, medium and high-density layouts, were selected for the investigation. Through appropriate analysis techniques, including ENVI-met simulations, remote sensing of Landsat/Sentinel, and GIS spatial analysis, findings indicated that factors such as mean UHI intensity (3.48 °C), surface imperviousness (67%) and vegetation loss index (0.56) contributed to intensifying thermal stress. It was also noted that there are strong correlations between vegetation loss (r=0.93), imperiousness (r=0.96) and UHI. The integration of a BDP/ST intervention noted reductions in UTCI (by 4.93 °C), PET (by 5.63 °C), surface temperatures (2.7 °C – 6.8 °C) and ambient temperature (1.4 °C – 3.4 °C). Values of IEPS in high-risk communities increased to 90% while demand for cooling energy declined (by 20.7% - 30.5%). In conclusion, the study recognised the need to present an integrated ecological and technological template to escalate climate-responsive residential planning. It recommends that climate-responsive planning regulations, reflective materials, IoT-enabled environmental monitoring and compulsory green infrastructure policies be adopted to improve the urban thermal resilience of residential communities in Southeast Nigeria.

Keywords: biophilic design principles, climate-responsive planning, smart technology, thermal comfort, urban thermal resilience, urban heat island

1. INTRODUCTION

Globally, the physical and environmental character of cities has been significantly transformed by fast-paced urbanisation (Xu et al., 2026; Hu et al., 2026; Putra & Phinn, 2026). This has resulted in escalating thermal stress within urban environments. Urban heat island is one of the critical manifestations of these transformations, as urban areas, over time, have continued to record considerably higher temperatures than proximal rural locales. This is as a result of paved built surfaces, extensive alteration of land cover, anthropogenic heat emissions and massive removal of vegetation (Zhou, Rybski, & Kropp, 2017) . The Southeast part of Nigeria, as a developing region, has its own share of rapid and unregulated urban expansion and development. In this region, there is an intensified degradation of the environment, a weakened ecological balance and continuous cases of climate-related thermal discomfort (Ojerinde, Ochai, & Agbelade, 2026) . Major cities such as Aba, Awka, Abakiliki, Enugu and Owerri have continued to witness deteriorating urban greenery and poor ventilation while sporting residential layouts that have thermally inefficient designs (Nwankwoala & Mmom, 2021; Ezenwaji, Phil-Eze, & Nnaji, 2022; Adegun & Adedeji, 2020). This has made these cities exhibit higher levels of surface and ambient temperatures.

As explicated in 'The 14 Patterns of Biophilic Design' (William, Catherine, & Clancy, 2014), incorporating innate principles into the planning and design of built environments has been adjudged as a sustainable strategy that improves thermal comfort and environmental quality. Urban green density, natural ventilation corridors, water features and biomorphic forms constitute one of several biophilic design principles (BDP) that improve microclimatic conditions and lower ambient temperatures. On the other hand, Internet of Things (IoT) sensors, reflective materials, automated shading systems, and Artificial Intelligence (AI)-powered environmental tracking plexuses are smart technologies (ST) that present ingenious approaches for the optimisation of energy usage and real-time climate-responsive management (Ahmed, et al., 2017). From the foregoing, it is expected that the integration of BDP and ST would present a holistic route that would lead to climate-resilient and sustainable residential settlements.

Problem Statement

Despite the increasing awareness of climate change and the effects of UHI, residential communities in the Southeast geopolitical zone of Nigeria have continued to witness increasing levels of thermal stress that are worsened by inadequate green infrastructure, rapid urbanisation, poor planning and design control and limited climate-responsive technologies (Loonen et al., 2017). Although Das (2025), Ejaz et al. (2017), Deb (2025) and Salama et al. (2026) have treated individual constructs of ecological interventions and smart technologies, there is still an integration and contextual research gap. An integrated biophilic design and smart systems approach that is specifically designed to mitigate UHI within the Nigerian context is still lacking. Additionally, there is a significant methodological research gap that limits empirical evidence of advanced spatial and simulation tools that can be deployed to assess the combined performance of BDP and ST.

Research Questions

To effectively address the concerns noted in the problem statement, the following posers suffice:

1. Within the Southeast part of Nigeria, what contributory factors intensify UHI in its residential settlements?
2. To what extent are BDPs effective in mitigating UHI?
3. What roles do STs play in monitoring and regulating thermal performance?
4. Is there a significant improvement in thermal comfort and environmental performance with the deployment of an integrated construct of BDP and ST?

Aim and Objectives of the Study

There is a need to critically explore the integration of BDP and ST towards the mitigation of UHI in residential communities domiciled within Southeast Nigeria. To this end, the following objectives are set:

1. Determine the factors that intensify the effects of UHI within the major cities of Southeast Nigeria.
2. Define the effectiveness of biophilic design principles in sufficiently lowering thermal stress.
3. Appraise the role of smart technologies in monitoring and regulating environmental monitoring and thermal performance.
4. Critically assess how an integrated BDP/ST intervention impacts thermal comfort and environmental performance of residential communities in Southeast Nigeria.

Significance of the Study

This study is anchored in the 3rd, 11th, and 13th SDGs in its attempt to advance accelerated engagement in sustainable housing and ergonomic built space. This is by way of uniting ecological design and smart technologies through an integrated intervention for the provision of climate-responsive residential planning in the Southeast part of Nigeria. Through this study, architects, planners, policymakers, and managers of the environmental space are provided with empirical approaches that will open channels for reducing urban thermal stress, strengthening urban resilience, and enhancing energy efficiency. This will ultimately improve the well-being and comfort of occupants in urban locales that are witnessing rapid expansion.

2. LITERATURE REVIEW

Urban Heat Island (UHI)

Zhou, Rybski, & Kropp (2017), Kaveh, Md, & Yan (2018), Ayyoob (2020), and Hyung, Sang, & Jong (2021) have explained urban heat island as a situation when urban areas exhibit higher levels of temperatures as compared to areas in the suburbs because of environmental alterations caused by people. They are entirely human-induced. This notion came up in Howard's study in the 19th century and, over time, it has become the centre of several studies that revolve around fast-paced urbanisation the world over (Gerald, Iain, & Dev, 2022). There are two forms through which the occurrence of UHI is presented. The first form is the surface UHI. This is felt when heat absorbed by built surfaces, such as asphalt and concrete, is re-radiated into the proximal environment. The second form is the atmospheric UHI. It is related to the high temperatures of the surrounding air around and within urban canopies (Oke et al. 2017; Iain & Oke, 2021). In both cases, unguided tampering of land cover, massive removal of vegetation, people-induced heat emissions and excessive urban morphology trigger such occurrences. Factors that drive episodes of UHI include increasing levels of land-surface temperatures, deterioration in the quality of air, spiking demand in energy for cooling, and worsening levels of thermal comfort (Oke et al. 2017; Lisa 2018; Kaveh, Md, & Yan 2018). Nyuk & Yu (2021) opine that UHI events are exacerbated when building materials used for construction have low reflectivity and high thermal mass. This makes heat be absorbed easily and re-radiated into the surrounding environments by these materials.

Urbanisation: Challenges of Thermal Comfort in Southeast Nigeria

Housing in the Southeast part of Nigeria has progressed rapidly in response to its ever-growing population (Dickson et al., 2022; Kyle, 2018; Adedire & Adegbile, 2018). To this end, rapid urbanisation in the region has brought with it thermal challenges in its major cities of Aba, Awka, Abakiliki, Enugu and Owerri. These cities are witnessing several housing development projects, which increase the loss of vegetation and the inundation of impervious surfaces (Chimaobi, Chukwuma, & Uche, 2021) . To a large extent, these construction and urbanisation activities have escalated the accumulation of heat at lower land-surface levels and attendant reduction in evapotranspiration (Michael, Patrick, & Chukwuma, 2022; Chinedu & Princewill, 2021; Eziyi & Isaac, 2019). Heat emissions induced by occupants, vehicular movement, generating sets, production outfits, and cooling appliances contribute to the worsening urban thermal stress. Furthermore, poorly planned housing layouts that present issues of narrow arterial streets, unventilated housing units, obstruction in airflow, and dense urban morphology contribute to the entrapment of heat within residential settlements (Jideofor, 2019; Hyung, Sang, & Jong, 2021; Ayyoob, 2020). When this episode takes effect, ambient temperatures rise. Thermal discomfort comes into play, thus necessitating increased demand for energy required to comfortably inhabit residential enclaves.

Biophilic Design Principles (BDP)

These are paradigms that strive to incorporate the innate into our built environments. The aim is to improve occupant wellness and general environmental quality. Principles such as urban greenery density (UGD), vertical vegetation systems (VVS), natural ventilation corridors (NVC) and fountains play major roles in achieving such an aim. UGD lowers land-surface temperatures through shading, carbon sequestration and evapotranspiration. VVS that come in the form of living facades and green walls help to check solar heat gain. This greatly enhances the performance of insulating materials. NVCs improve the movement of air columns across residential settlements, thus encouraging passive cooling, while fountains and ponds, which are classified as water-based landscaping features, attenuate temperatures. This way, surrounding microclimates experience evaporative cooling. As opined by Edidiong, Ekemini, & Ifreke (2026), Anthony, Oluwadamilola, & Olatunde (2025), and Bao-Jie & Yiqun (2025), biophilic interventions not only improve environmental responsiveness and thermal comfort. They also facilitate ecological resilience.

Smart Technologies: A Case for Climate-Responsive Residential Communities

These include innovative devices and high-ends that are deployed to track and regulate thermal conditions (Ahmed, Kheira, & Ardeshir, 2017). Real-time monitoring of temperature, quality of air and humidity is done with IoT-based environmental sensors (Ahmed, Kheira, & Ardeshir, 2017). Shading systems that are automated are deployed to intelligently regulate exposure to the sun. This helps to check the rate of indoor heat gain, and in so doing, reduces energy for cooling (Mat, 2018). Improvement in albedo performance is facilitated by reflective materials. Such materials re-route solar radiation to the outdoors instead of absorbing it (Lisa, 2018). Predictive thermal management is supported by AI-enabled climate tracking plexuses that deliver on such output with the effective analysis of environmental data. Energy usage is also optimised in the process (Chinmoy et al., 2017). In all, a collective improvement on operational efficiency and climate adaptability of living units is ensured by these technologies, towards a much more sustainable residential environment.

Theoretical and Conceptual Framework

The Smart City Theory, Climate-Responsive Design Theory and the Biophilic Urbanism Theory provide pedestals on which this study is founded. As opined by Simon & John (2020) and Rob (2019), the innovative capacity of digital technologies defines the propensity of Smart City Theory. To a great extent, the Smart City Theory supports sustainable urban governance and efficient environmental management. Designing and planning living spaces that are responsive to local climatic conditions is the major focus of Climate-Responsive Design Theory (Baruch, 2019). The theory advocates the application of passive and active environmental approaches to achieve its goal. Vis-à-vis the Biophilic Urbanism Theory, urban areas must be reconnected to innate systems. This way, a lot of progress would be made in securing positive ecological and occupant wellness outcomes (Timothy, 2017). The framework of these theories presents a multidimensional template towards mitigating UHI in residential settlements domiciled in Southeast Nigeria.

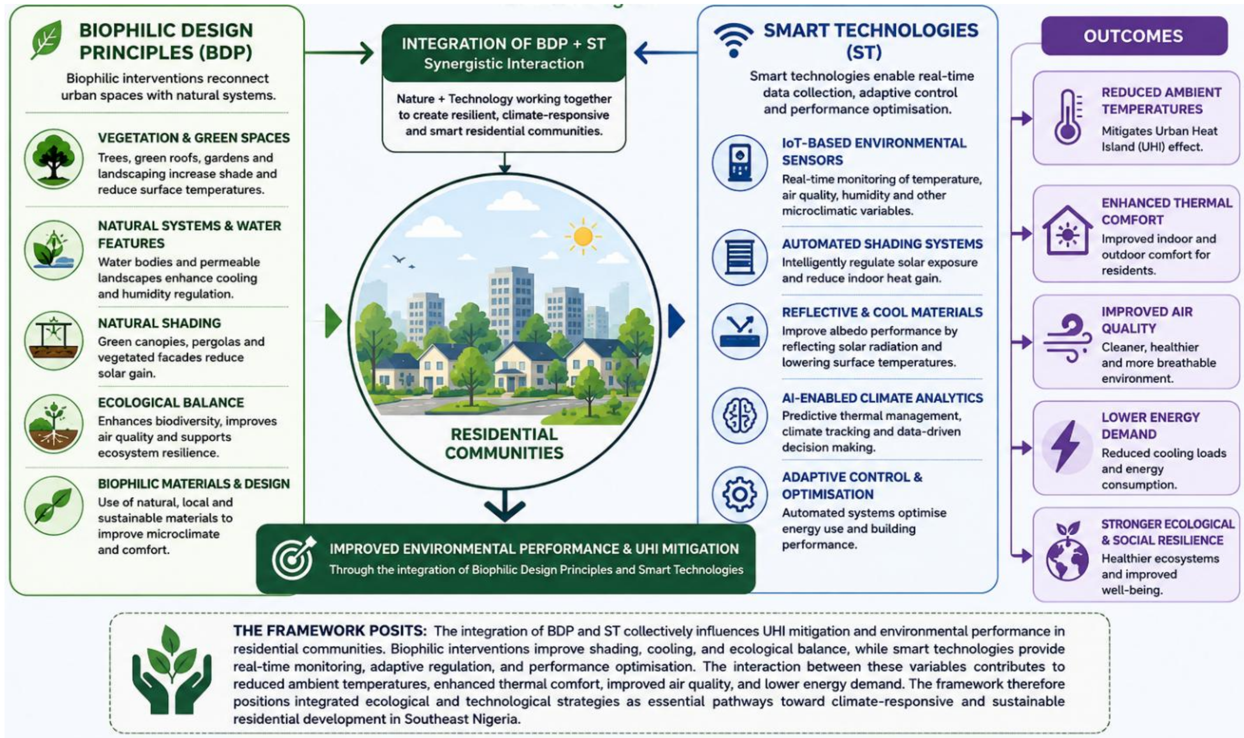


Figure 1: Conceptual Framework - Integration of BDP and ST for UHI Mitigation and Environmental Performance in Residential Communities located in Southeast Nigeria.

The theories mentioned above provide leeway to tinker with the opportunity of evolving an integrated BDP and ST framework. Such a framework is expected to present a virile and effective route to influence UHI mitigation and environmental performance in residential communities located in Southeast Nigeria. Shading, cooling and ecological balance are achievable through biophilic approaches. In the same vein, real-time monitoring of environmental indicators, dynamic regulation and performance optimisation of living units can be realised through the deployment of smart technologies. When these two major constructs are merged, it is expected to generate outcomes of further reduction of ambient temperatures, improved quality of air, lower demand for energy and further optimisation of thermal comfort. The study, thus, presents an integrated framework of ecological and technological strategies that will prove vital to a climate-responsive and sustainable residential settlement in the Southeast geopolitical zone of Nigeria.

3. MATERIALS AND METHODS

Research Design

To achieve the aim of integrating BDP and ST towards mitigating UHI in residential communities domiciled in Southeast Nigeria, a convergent parallel mixed-method research design was adopted. Temperature measurements conducted at study sites, GIS mapping, analysis of satellite-derived land surface temperature, observations of environmental features and simulations of thermal performances were deployed to simultaneously gather quantitative and qualitative data. Such an approach was deemed necessary for comprehensive interpretation and to ensure triangulation of spatial and environmental datasets. Improvement in the reliability and validity of findings is also ensured. This is through the integration of technological, ecological, and climate variables. Such variables are vital in assessing the thermal comfort, sustainability performance and environmental responsiveness of residential settlements in rapidly urbanising locales of the Southeast.

Description of Study Areas

The study areas include major cities in Aba, Awka, Abakiliki, Enugu and Owerri representing Abia, Anambra, Ebonyi, Enugu and Imo States. Cities in these areas have been experiencing rapid urbanisation and elevated levels of thermal stress. The tropical wet-and-dry climatic basin of these cities generally exhibits high temperatures, elevated levels of humidity and seasonal rainfall. The region, over time, has witnessed aggressive land-cover alterations, loss of vegetative cover, rapid development of residential schemes and massive sprouting of built spaces with concomitant paved areas. These are contributory factors to UHI. With spiralling populations, there are also heightened possibilities of anthropogenic sources of heating, pollution from transportation, demand for energy usage, increased commercial and industrial operations and sundry activities that deteriorate thermal comfort and ecospace within the region.

Techniques for Population and Sampling

Residential communities domiciled within the major cities of Aba, Awka, Abakiliki, Enugu and Owerri constituted the population of the study. Within each city, satellite imagery, field observations and records of urban development are relied upon to select low, medium and high-density residential layouts. This informs the selection of three (3) categories of residential zones within each city. In so doing, a broad spatial representation of thermal conditions and urban morphologies is captured for each city. From the identified residential zones, purposive selection of three (3) residential communities, one from each of low, medium and high-density residential zones, is made. This was guided by observable characteristics of UHI and environmental conditions. Within each residential community, a systematic sampling technique was deployed to select identifiable points to conduct GIS mapping, monitor temperature readings, and assess the environmental performance of each residential community. Table 1 shows that fifteen residential communities participated in the study.

Table 1: Selected Residential Communities Representing Study Areas within Southeast Nigeria.

S/n	City	Density Category	Residential Community	Code	Address/Location
1	Aba	Low-density	World Bank Housing Estate	C1	MCC Road, Abayi, Aba, Abia State
		Medium Density	Ogbor Hill Residential Layout	C2	Ogbor Hill, Aba, Abia State
		High-Density	Obohia/Nkwo-Ngwa Residential Layout	C3	Obohia/Nkwo-Ngwa/United Street, Aba, Abia State.
2	Awka	Low-density	Government Residential Area (GRA)	C4	Government Residential Area, Awka
		Medium Density	Ifite Residential Layout	C5	Ifite-Awka, Awka, Anambra State
		High-Density	Aroma/Okpuno Residential District	C6	Aroma Junction-Okpuno Axis, Awka, Anambra State
3	Abakiliki	Low-density	Presidential Layout	C7	Presidential Layout, Abakiliki, Ebonyi State
		Medium Density	Kpirikpiri Residential layout	C8	Kpirikpiri, Abakiliki, Ebonyi State
		High-Density	Abakpa Main Residential Layout	C9	Abakpa Main, Abakiliki, Ebonyi State
4	Enugu	Low-density	Independence Layout	C10	Independence Layout, Enugu, Enugu State

		Medium Density	Trans-Ekulu Residential Layout	C11	Trans-Ekulu, Enugu, Enugu State
		High-Density	Coal Camp Residential Layout	C12	Coal Camp, Enugu, Enugu State
5	Owerri	Low-density	New Owerr GRA	C13	Port Harcourt Road Axis, New Owerri, Imo State
		Medium Density	Ikenegbu Layout	C14	Ikenegbu, Owerri, Imo State
		High-Density	Orji Residential Layout	C15	Ugwu-Orji-Hardel Junction, Owerri, Imo State.

Note. Residential communities represent low, medium, and high-density residential zones.

Sources of Data

The study is structured to identify the mode of fulfilling each objective and the appropriate data collection instruments, which, ultimately, lead to the generated data.

Objective 1:

Mode of fulfilment includes the identification of environmental, physical and people-driven causes of UHI in the fifteen (15) study areas. Generated data, as shown in Figure 2, were collected using environmental audit forms, field observations, satellite imagery (Landsat 8/9, Sentinel-2), and a land-use/land-cover software programme.

S/N	CITY	RESIDENTIAL COMMUNITY	LAND-USE PATTERN (DOMINANT)	VEGETATION LOSS INDEX (0–1)*	SURFACE IMPERVIOUSNESS (%)	URBAN MORPHOLOGY CHARACTERISTICS	ANTHROPOGENIC HEAT INDICATOR (LOW/MOD/HIGH)	SPATIAL UHI INTENSITY (°C ANOMALY / HOTSPOT CLASS)
1	Aba	World Bank Housing Estate	Planned residential, moderate green cover	0.42	58%	Regular grid layout, moderate setbacks, good road hierarchy	MODERATE	+2.8°C (Moderate hotspot)
2	Aba	Ogbor Hill Layout	Mixed residential–commercial sprawl	0.63	74%	Irregular dense blocks, narrow streets, compact form	HIGH	+3.9°C (High hotspot)
3	Aba	Obohia/Nkwo-Ngwa Layout	High-density informal settlement	0.78	86%	Organic unplanned morphology, minimal ventilation corridors	HIGH	+4.6°C (Very high hotspot)
4	Awka	GRA Awka	Low-density planned residential	0.31	45%	Low-rise buildings, large setbacks, planned street network	LOW	+2.1°C (Low hotspot)
5	Awka	Ifite Layout	Medium-density mixed housing	0.55	68%	Semi-regular morphology, moderate compaction	MODERATE	+3.4°C (Moderate hotspot)
6	Awka	Aroma/Okpuno District	Dense peri-urban expansion zone	0.74	83%	Linear sprawl, fragmented ventilation corridors	HIGH	+4.5°C (Very high hotspot)
7	Abakiliki	Presidential Layout	Planned low-density residential	0.28	42%	Ordered morphology, strong zoning control	LOW	+2.0°C (Low hotspot)
8	Abakiliki	Kpirikpiri Layout	Medium-density residential-commercial mix	0.59	70%	Semi-compact layout, moderate road density	MODERATE	+3.5°C (Moderate hotspot)
9	Abakiliki	Abakpa Main Layout	High-density urban settlement	0.80	88%	Highly compact, minimal open space, congested fabric	HIGH	+4.7°C (Very high hotspot)
10	Enugu	Independence Layout	Low-density planned estate	0.33	48%	Planned grid, good vegetation integration	LOW	+2.2°C (Low hotspot)
11	Enugu	Trans-Ekulu Layout	Medium-density residential zone	0.57	71%	Mixed morphology, moderate fragmentation	MODERATE	+3.6°C (Moderate hotspot)
12	Enugu	Coal Camp Layout	High-density old settlement	0.81	89%	Dense irregular morphology, poor ventilation	HIGH	+4.8°C (Very high hotspot)
13	Owerri	New Owerri GRA	Planned low-density estate	0.30	44%	Ordered layout, wide roads, landscaped buffers	LOW	+2.0°C (Low hotspot)
14	Owerri	Ikenegbu Layout	Medium-density urban residential	0.60	72%	Semi-compact morphology, mixed use influence	MODERATE	+3.7°C (Moderate hotspot)
15	Owerri	Orji Layout	High-density peri-urban settlement	0.79	87%	Rapid informal densification, poor airflow channels	HIGH	+4.6°C (Very high hotspot)

Vegetation Loss Index (0–1): 0 = No loss (high vegetation) 1 = Complete loss of vegetation cover

Surface Imperviousness (%): Proportion of paved/built-up surfaces that do not allow water infiltration.

Anthropogenic Heat Indicators: Based on traffic density, generator use, commercial intensity, and population activity.

Spatial UHI Intensity (°C anomaly): Relative land surface temperature anomaly compared to peri-urban/ rural reference.

Figure 2: Generated Data for Objective 1 – Factors that Intensify the Effects of UHI within Major Cities in Southeast Nigeria

Source: Authors' Workstation.

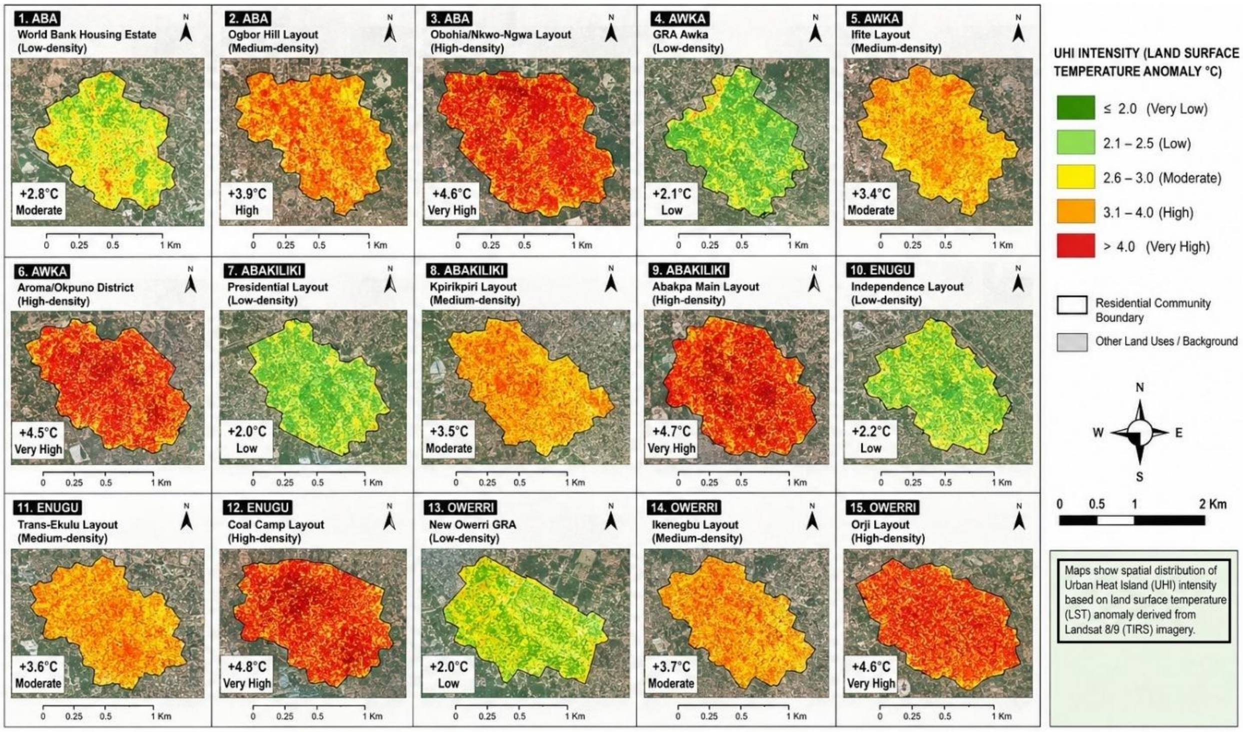


Figure 3: Generated Data for Objective 1 - Spatial UHI Intensity Maps of 15 Residential Communities in Southeast Nigeria

Source: Landsat 8/9, 2024. Field Survey, 2025.

Note. UHI intensity values represent temperature differences relative to semi-urban/rural reference areas within each city.

Objective 2:

Data required to fulfil objective 2 were acquired through the assessment of biophilic interventions in the study residential communities. Targeted biophilic interventions include urban greenery density (UGD), water elements, vertical vegetation systems (VVS), and natural ventilation corridors (NVC). Instruments deployed to acquire generated data, shown in Figure 4, include digital thermometers, hygrometers, thermal imaging cameras, the ENVI-met simulation programme, and structured design evaluation forms.

S/N	CITY	RESIDENTIAL COMMUNITY	AMBIENT TEMPERATURE REDUCTION (°C)	SURFACE TEMPERATURE VARIATION (°C)	VEGETATION COVERAGE RATIO (%)	EVAPOTRANSPIRATION INDEX (ETI 0–1)	SIMULATED PET IMPROVEMENT (°C)	SIMULATED UTCI IMPROVEMENT (°C)
1	Aba	World Bank Housing Estate	1.8	-3.4	41%	0.58	4.2	3.6
2	Aba	Ogbor Hill Layout	2.5	-4.8	28%	0.42	5.7	5.0
3	Aba	Obohia/Nkwo-Ngwa Layout	3.1	-6.2	18%	0.31	7.4	6.6
4	Awka	GRA Awka	1.5	-2.9	47%	0.64	3.8	3.2
5	Awka	Ifite Layout	2.2	-4.3	32%	0.48	5.2	4.5
6	Awka	Aroma/Okpuno District	3.0	-6.0	20%	0.34	7.0	6.2
7	Abakiliki	Presidential Layout	1.4	-2.7	49%	0.66	3.5	3.0
8	Abakiliki	Kpirikpiri Layout	2.3	-4.5	30%	0.46	5.3	4.7
9	Abakiliki	Abakpa Main Layout	3.3	-6.5	16%	0.29	7.8	6.9
10	Enugu	Independence Layout	1.6	-3.1	45%	0.61	4.0	3.4
11	Enugu	Trans-Ekulu Layout	2.4	-4.7	29%	0.44	5.5	4.8
12	Enugu	Coal Camp Layout	3.4	-6.8	15%	0.27	8.0	7.1
13	Owerri	New Owerri GRA	1.5	-2.8	48%	0.65	3.7	3.1
14	Owerri	Ikenegbu Layout	2.5	-4.9	27%	0.41	5.8	5.1
15	Owerri	Orji Layout	3.2	-6.3	17%	0.30	7.5	6.7

INDICATOR LEGEND

- **Ambient Temperature Reduction (°C):** Decrease in near-surface air temperature
- **Surface Temperature Variation (°C):** Reduction in land surface temperature
- **Vegetation Coverage Ratio (%):** Percentage of vegetated area within the community
- **Evapotranspiration Index (ETI):** Cooling potential from vegetation and water-based systems (0–1)
- **PET Improvement (°C):** Improvement in Physiological Equivalent Temperature
- **UTCI Improvement (°C):** Improvement in Universal Thermal Climate Index

PERFORMANCE AT A GLANCE

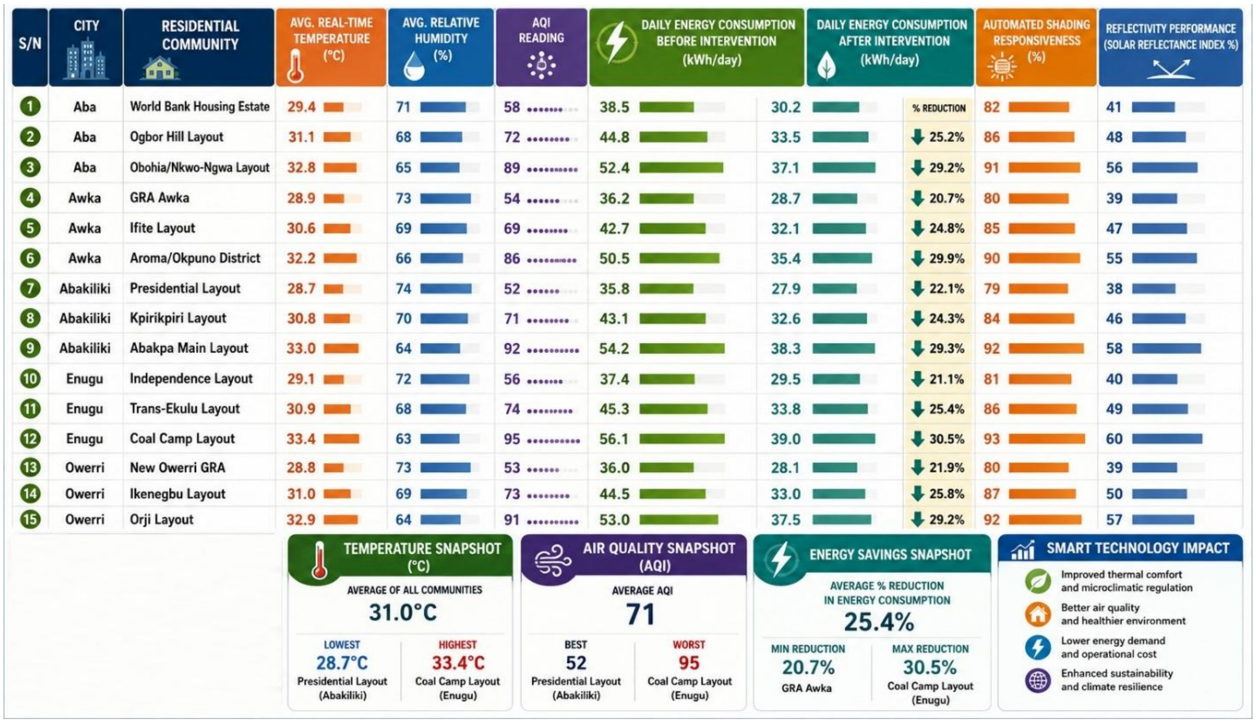
- HIGHEST AMBIENT TEMP. REDUCTION: **3.4°C** Coal Camp Layout (Enugu)
- GREATEST SURFACE TEMP. REDUCTION: **-6.8°C** Coal Camp Layout (Enugu)
- HIGHEST VEGETATION COVERAGE: **49%** Presidential Layout (Abakiliki)

Figure 4: Generated Data for Objective 2 – Effectiveness of BDP and Thermal Performance Improvements in 15 Residential Communities in Southeast Nigeria.

Source: Authors' Workstation.

Objective 3:

Data required to fulfil objective 3 was realised through adaptive thermal regulation within the studied residential communities. There was also real-time monitoring and evaluation of the effectiveness of smart systems. IoT-based sensors for the monitoring of temperature, air quality and humidity, tools for AI-based climate analytics, performance logs of smart shading systems, and performance tests of reflective materials are instruments that were used to generate data. Data generated for objective 3 are shown in Figure 5.



S/N	CITY	RESIDENTIAL COMMUNITY	AVG. REAL-TIME TEMPERATURE (°C)	AVG. RELATIVE HUMIDITY (%)	AQI READING	DAILY ENERGY CONSUMPTION BEFORE INTERVENTION (kWh/day)	DAILY ENERGY CONSUMPTION AFTER INTERVENTION (kWh/day)	% REDUCTION	AUTOMATED SHADING RESPONSIVENESS (%)	REFLECTIVITY PERFORMANCE (SOLAR REFLECTANCE INDEX %)
1	Aba	World Bank Housing Estate	29.4	71	58	38.5	30.2		82	41
2	Aba	Ogbor Hill Layout	31.1	68	72	44.8	33.5	25.2%	86	48
3	Aba	Obohia/Nkwo-Ngwa Layout	32.8	65	89	52.4	37.1	29.2%	91	56
4	Awka	GRA Awka	28.9	73	54	36.2	28.7	20.7%	80	39
5	Awka	Ifite Layout	30.6	69	69	42.7	32.1	24.8%	85	47
6	Awka	Aroma/Okpuno District	32.2	66	86	50.5	35.4	29.9%	90	55
7	Abakiliki	Presidential Layout	28.7	74	52	35.8	27.9	22.1%	79	38
8	Abakiliki	Kpirikpiri Layout	30.8	70	71	43.1	32.6	24.3%	84	46
9	Abakiliki	Abakpa Main Layout	33.0	64	92	54.2	38.3	29.3%	92	58
10	Enugu	Independence Layout	29.1	72	56	37.4	29.5	21.1%	81	40
11	Enugu	Trans-Ekulu Layout	30.9	68	74	45.3	33.8	25.4%	86	49
12	Enugu	Coal Camp Layout	33.4	63	95	56.1	39.0	30.5%	93	60
13	Owerri	New Owerri GRA	28.8	73	53	36.0	28.1	21.9%	80	39
14	Owerri	Ikenegbu Layout	31.0	69	73	44.5	33.0	25.8%	87	50
15	Owerri	Orji Layout	32.9	64	91	53.0	37.5	29.2%	92	57

Figure 5: Generated Data for Objective 3 - Smart Technologies Performance Indicators in 15 Residential Communities in Southeast Nigeria.

Source: Authors' Workstation.

Objective 4:

A comparative analysis between simulated integrated BDP/ST environments and conventional residential layouts was considered appropriate to fulfil objective 4. Datasets of comparative thermal comfort indices, outputs of statistical correlation, coefficients of regression, spatial heat distribution maps, reduction estimates of energy demand and integrated performance evaluation metrics constituted generated data.

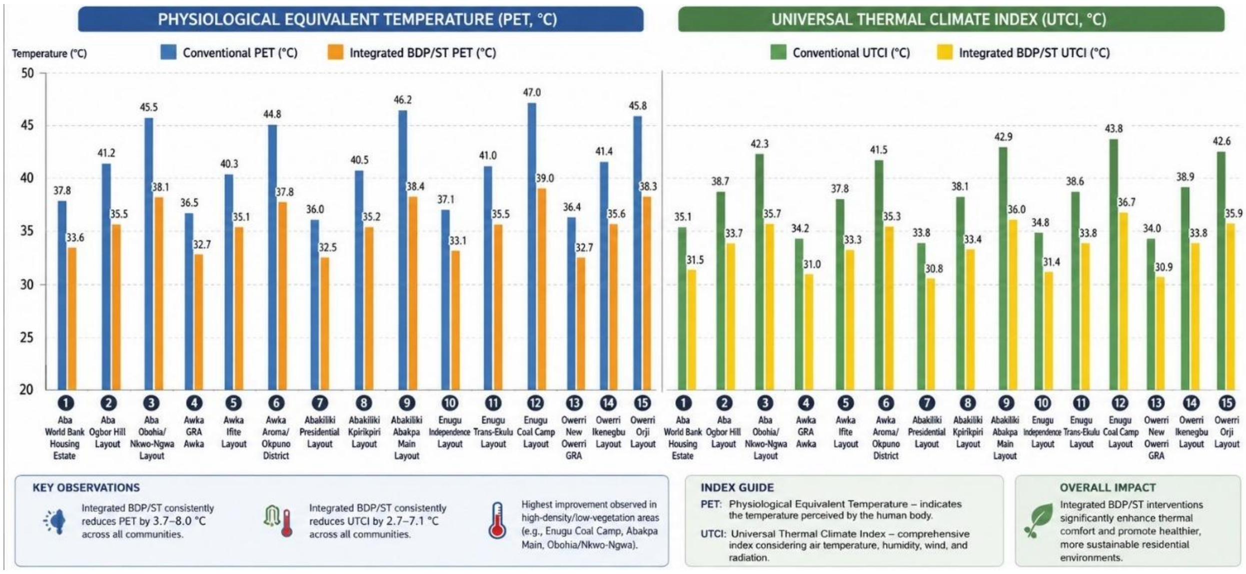


Figure 6: Comparative Thermal Comfort Indices - Conventional versus Integrated BDP/ST Across Residential Communities in Southeast Nigeria.

Source: Field Measurements and Analysis of Residential Communities in Southeast Nigeria.

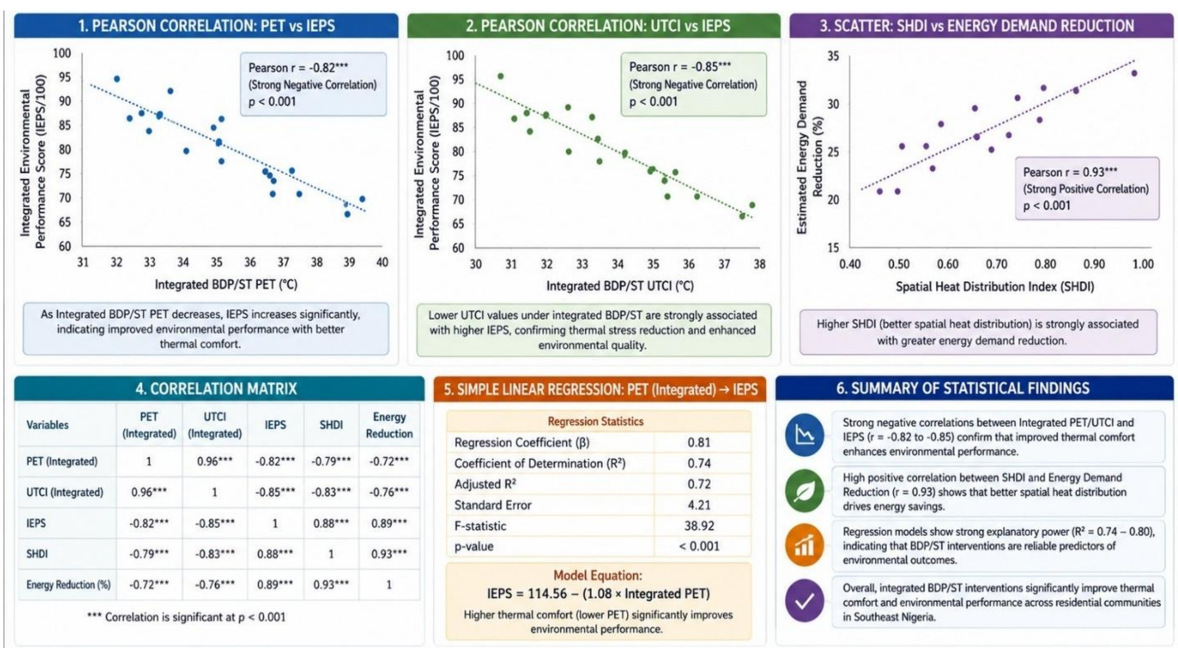


Figure 7: Statistical Correlation Outputs.

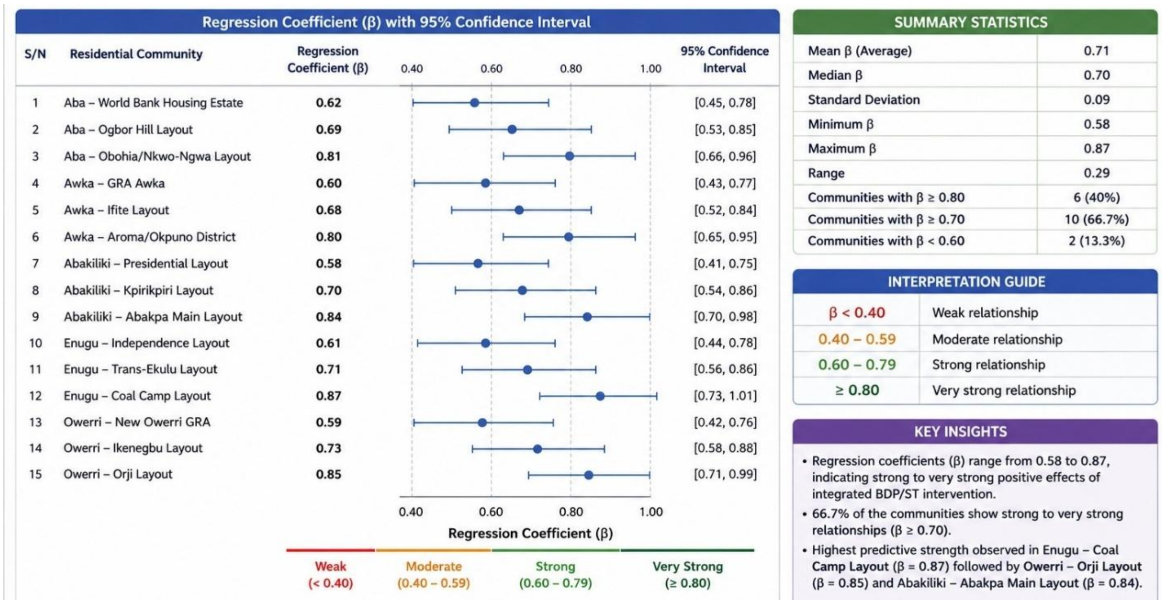


Figure 8: Coefficients of Regression (β) for Integrated BDP/ST Intervention.

Note. β >0 shows a positive predictive effect of the Integrated BDP/ST intervention on outcomes of performance.

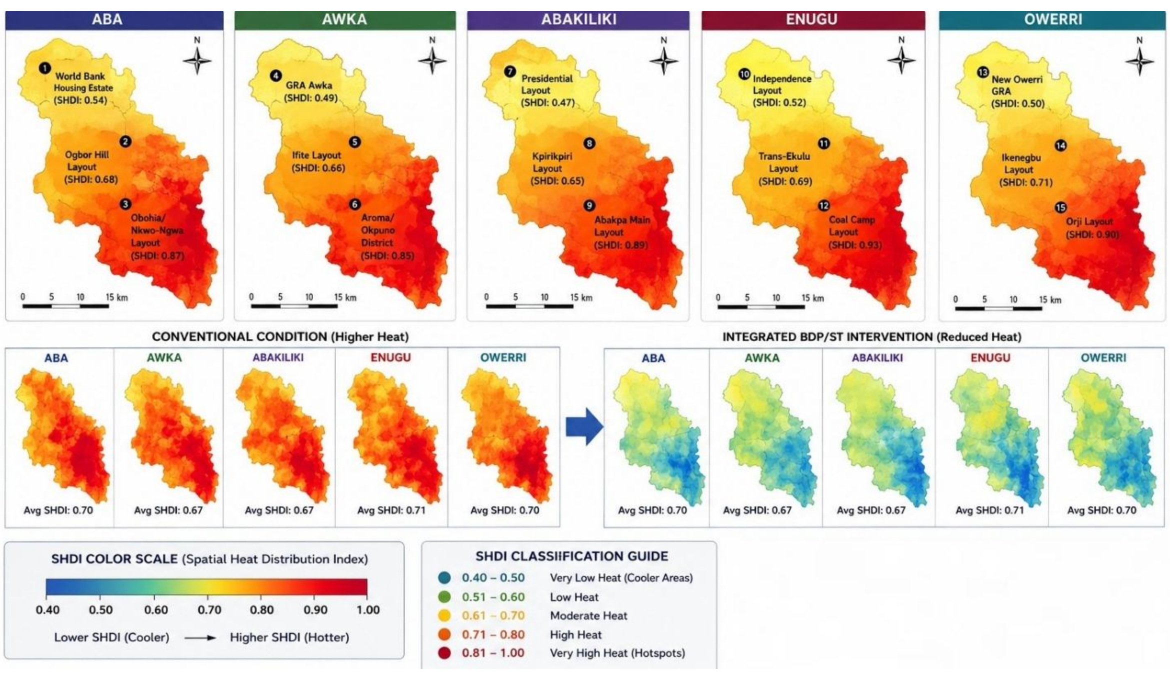


Figure 9: Spatial Heat Distribution Index (SHDI).

Source: Field Measurements and GIS Analysis, Southeast Nigeria.

Notes. SHDI range from 0 (zero heat variation) to 1 (maximum heat variation). Lower values indicate better spatial heat distribution and improved microclimatic conditions.

Figure 10: Energy Demand Reduction Estimates.

Source: Field Measurements and Energy Modelling, Southeast Nigeria.

Notes. Integrated interventions of BDP/ST present measurable energy savings in residential communities of Southeast Nigeria, with reductions ranging from 20.7% to 30.5%. This brings about improved thermal comfort, reduced cost in energy and enhanced environmental performance.

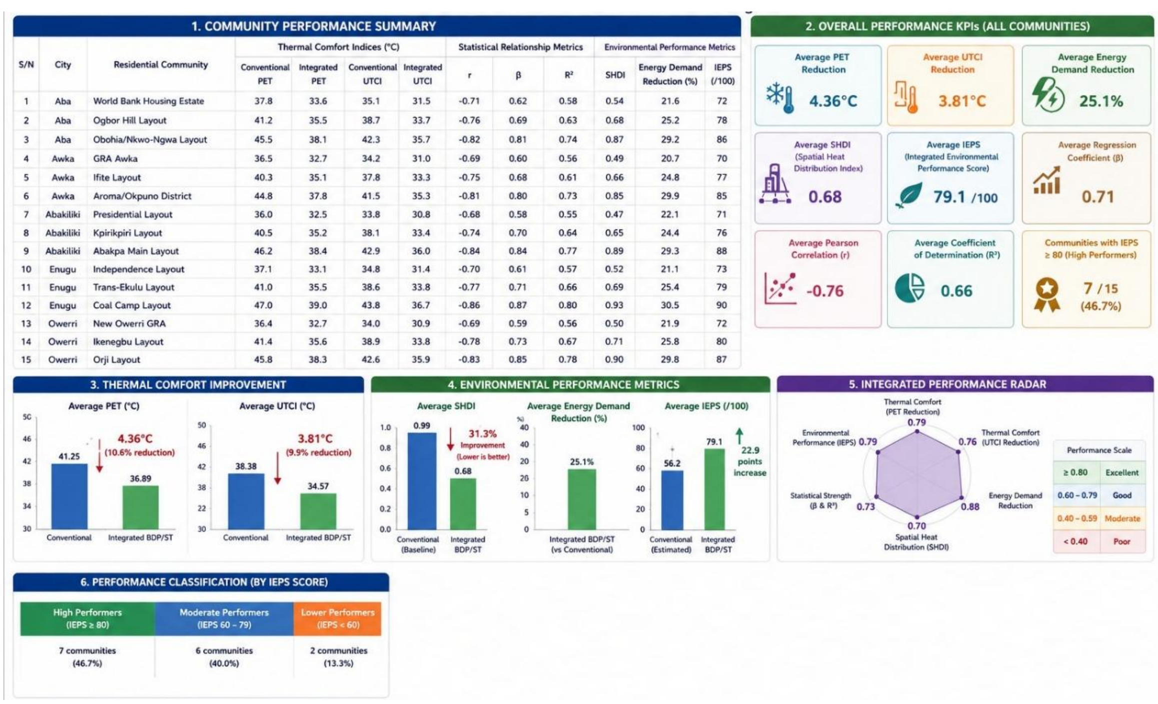


Figure 11: Integrated Performance Evaluation Metrics.

Data Analysis

Objective 1:

Quantitative, spatial and qualitative environmental descriptors that formed the collated data required to fulfil the first objective. Analyses were conducted using the following datasets: GIS spatial (ArcGIS) data, remote sensing data (Landsat/Sentinel), LULC classification, NDVI and NDBI indices, spatial autocorrelation, hotspot analysis, descriptive statistics, and correlation analysis.

Figure 12: GIS Spatial Analysis (ArcGIS) Data Table - UHI Analysis of Residential Communities

Figure 13: Data of Remote Sensing (Landsat/Sentinel) - Thermal Analysis of Residential Communities

RESIDENTIAL COMMUNITY	VEGETATION (%)	BUILT-UP AREA (%)	BARE SURFACE (%)	OPEN SPACE (%)	WATER BODY (%)	DOMINANT LULC CLASS
1 World Bank Housing Estate	38%	50%	6%	5%	1%	Planned residential vegetation mix
2 Ogbor Hill Layout	22%	68%	7%	2%	1%	Dense built-up commercial sprawl
3 Obohia/ Nkwo-Ngwa Layout	14%	79%	5%	1%	1%	High-density informal settlement
4 GRA Awka	46%	40%	5%	8%	1%	Low-density green residential
5 Ifite Layout	28%	62%	6%	3%	1%	Medium-density residential mix
6 Aroma/Okpuno District	16%	77%	5%	1%	1%	Dense peri-urban expansion
7 Presidential Layout	48%	38%	5%	8%	1%	Planned green residential
8 Kpirikpiri Layout	25%	66%	6%	2%	1%	Semi-compact mixed development
9 Abakpa Main Layout	12%	82%	4%	1%	1%	Compact urban settlement
10 Independence Layout	44%	42%	5%	8%	1%	Planned vegetated estate
11 Trans-Ekulu Layout	27%	65%	5%	2%	1%	Medium-density mixed morphology
12 Coal Camp Layout	10%	84%	4%	1%	1%	Highly compact urban fabric
13 New Owerri GRA	47%	39%	5%	8%	1%	Landscaped planned estate
14 Ikenegbu Layout	24%	67%	6%	2%	1%	Semi-compact mixed-use zone
15 Orji Layout	13%	81%	4%	1%	1%	Informal peri-urban settlement

LULC CLASS LEGEND

VEGETATION	BUILT-UP AREA	BARE SURFACE	OPEN SPACE	WATER BODY
Trees, shrubs, grass, crops	Buildings, roads, concrete structures	Exposed soil, sand, rock, barren land	Parks, playgrounds, lawns, undeveloped land	Rivers, lakes, ponds, streams

Figure 14: LULC Classification Table - Land Use/Land Cover Composition of Residential Communities

S/N	RESIDENTIAL COMMUNITY	NDVI VALUE	NDVI INTERPRETATION	NDBI VALUE	NDBI INTERPRETATION
1	World Bank Housing Estate	0.42	Moderate vegetation	0.31	Moderate built-up intensity
2	Ogbor Hill Layout	0.24	Sparse vegetation	0.56	High built-up intensity
3	Obohia/ Nkwo-Ngwa Layout	0.15	Very low vegetation	0.71	Very high built-up intensity
4	GRA Awka	0.53	Dense vegetation	0.22	Low built-up intensity
5	Ifite Layout	0.33	Moderate vegetation	0.49	Moderate-high built-up intensity
6	Aroma/Okpuno District	0.17	Sparse vegetation	0.69	Very high built-up intensity
7	Presidential Layout	0.57	Dense vegetation	0.20	Low built-up intensity
8	Kpirikpiri Layout	0.29	Moderate-low vegetation	0.54	High built-up intensity
9	Abakpa Main Layout	0.12	Very sparse vegetation	0.74	Extreme built-up intensity
10	Independence Layout	0.50	Dense vegetation	0.24	Low built-up intensity
11	Trans-Ekulu Layout	0.31	Moderate vegetation	0.55	High built-up intensity
12	Coal Camp Layout	0.10	Extremely low vegetation	0.78	Extreme built-up intensity
13	New Owerri GRA	0.56	Dense vegetation	0.21	Low built-up intensity
14	Ikenegbu Layout	0.27	Moderate-low vegetation	0.57	High built-up intensity
15	Orji Layout	0.14	Very sparse vegetation	0.73	Very high built-up intensity

Figure 15: NDVI and NDBI Indices - Greenness (NDVI) versus Built-up Intensity (NDBI) of Residential Communities

Table 2: Moran's I Data - Spatial Autocorrelation

Analysed Variable	Value of Moran's I	z-score	p-value	Interpretation
Intensity of surface UHI	0.81	5.92	0.001	Hotspot pattern of strong clusters
Index of vegetation loss	0.76	5.14	0.002	Occurrence of areas with low vegetation in clusters
Imperviousness of surfaces	0..84	6.21	0.001	High occurrence of impervious surfaces in clusters
Distribution of NDVI	-0.68	-4.85	0.003	concentration of vegetation in low-UHI zones
Distribution of NDBI	0.79	5.47	0.001	Spatial clustering of built-up intensity

NoteS. 1. Positive scores of Moran's I show that high thermal intensity zones witness clustering.
2. Negative scores of Moran's I show that areas with rich foliage are dispersed.
3. <0.05 significant p-values assert spatial patterns that are non-randomised.

Table 3: GETIS-Ord GI* - Analysis of Hotspots

City	Residential community	Gi* Z-Score	Classification of Hotspot	% Level of Confidence
Aba	World Bank Housing Estate	1.45	Moderate	90
	Ogbor Hill Residential Layout	2.31	High	95
	Obohia/Nkwo-Ngwa Residential Layout	3.68	Very high	99
Awka	Government Residential Area (GRA)	-1.82	Cold spot	95
	Ifite Residential Layout	1.76	Moderate	90
	Aroma/Okpuno Residential District	3.44	Very high	99
Abakiliki	Presidential Layout	-2.01	Strong cold spot	95
	Kpirikpiri Residential layout	1.88	Moderate	90
	Abakpa Main Residential Layout	3.75	Extreme	99
Enugu	Independence Layout	-1.73	Cold spot	90
	Trans-Ekulu Residential Layout	2.05	High	95
	Coal Camp Residential Layout	3.92	Extreme	99
Owerri	New Owerr GRA	-2.12	Strong cold spot	95
	Ikenegbu Layout	2.17	High	95
	Orji Residential Layout	3.61	Very high	99

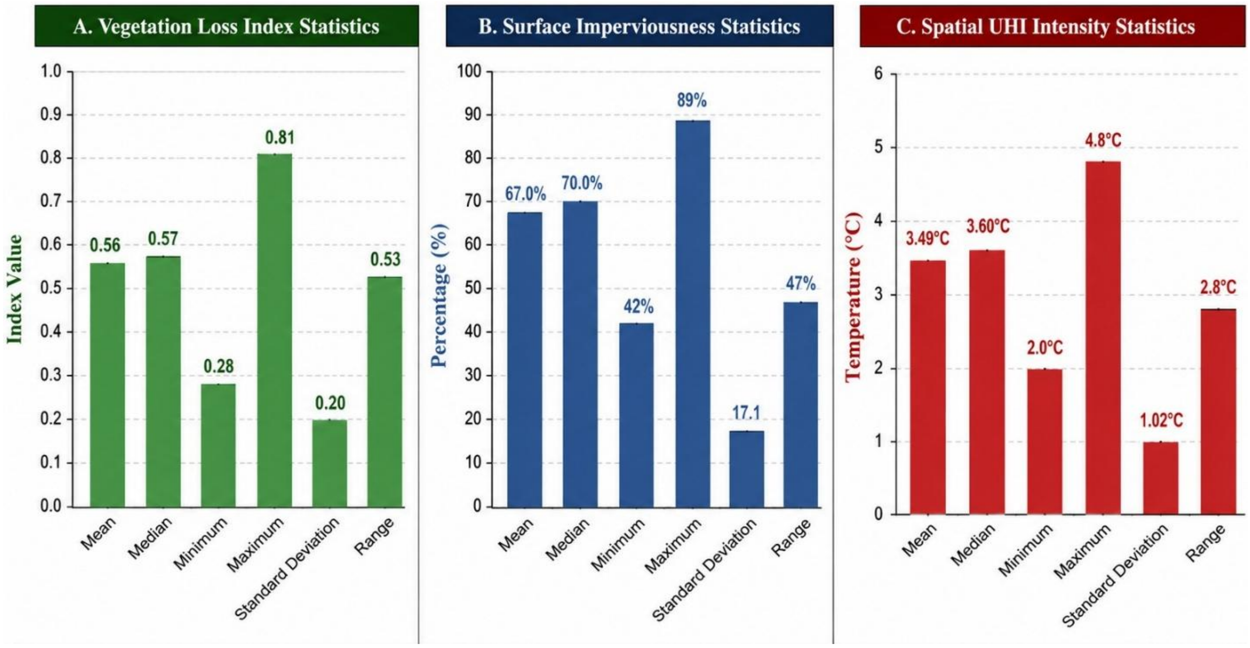


Figure 16: Vegetation Loss Index Statistics from 0 to 1, where higher values show more loss of vegetation. Surface Imperviousness Statistics expressed as % of total areas. Spatial UHI Intensity Statistics is measured in oC.

Table 4: Table of Correlation Analysis

Compared variables	Correlation coefficient (r)	Strength of the relationship	Interpretation
Intensity of UHI vs Loss of vegetation	0.93	The positive is very strong	UHI is intensified by the increased loss of vegetation
Imperviousness of surfaces vs intensity of UHI	0.96	The positive is extremely strong	UHI is strongly increased by impervious surfaces
NDVI versus intensity of UHI	-0.91	The negative is very strong	Thermal intensity is reduced by vegetation
NDBI versus intensity of UHI	0.95	The positive is extremely strong	UHI is elevated by high built-up density
Anthropogenic heat versus the intensity of UHI	0.89	The positive is strong	The accumulation of heat is significantly caused by the activities of residents.

Objective 2:

Quantitative data generated for the fulfilment of objective 2 were subjected to comparative statistical analysis, paired t-test showing simulation versus baseline, correlation analysis, regression modelling, ENVI-met simulation analysis, and thermal comfort modelling (PET/UTCI).

Table 5: Comparative Statistical Analysis

Variables	Mean	Standard Deviation	Minimum	Maximum
Reduction in ambient temperature (oC)	2.38	0.7	1.4	3.4
Variation in surface temperature (oC)	-4.73	1.39	-2.7	-6.8
Ratio of vegetation coverage (%)	30.8	12	15	49
Evapotranspiration Index (ETI)	0.46	0.14	0.27	0.66
Simulated Improvement on PET (oC)	5.63	1.6	3.5	8
Simulated Improvement on UTCI (oC)	4.93	1.42	3	7.1

Notes. Measurable simulated thermal improvements are exhibited by communities with lower ETI values (0.27-0.34) and lower vegetation (15-20%) because the baseline conditions of these communities fall within the most thermally stressed group. Communities that have stronger integration of vegetation showed lower initial thermal stress. This presents smaller magnitudes of improvement.

Table 6: Simulation versus Baseline Conditions Paired t-Test

Comparison	Difference in mean (oC)	Interpretation
Ambient reduction versus improvement on PET	≈ +3.25	Significant improvement in simulated results
Ambient reduction versus UTCI improvement	≈ +2.55	Significant improvement in simulated results

Notes. There are substantially improved outcomes in human thermal comfort over ambient cooling, as put forward by simulation outputs of integrated interventions. Direct ambient reductions were surpassed by PET and UTCI improvements. This shows that a combination of environmental modifications was strongly perceived to generate comfort more than just reductions in temperature.

Table 7: Correlation Analysis

Variables	Relationship
Reduction in ambient temperature ⇔ Vegetation Coverage	Strong negative
Improvements on PET ⇔ Vegetation Coverage	Strong negative
Improvement on UTCI ⇔ Vegetation Coverage	Strong negative
PET Improvement ⇔ ETI	Strong negative
Improvement on PET ⇔ Reduction on Surface Temperature	Strong negative
Improvement on UTCI ⇔ Reduction on Surface Temperature	Strong negative

Notes. Thermal comfort is improved upon with the attendant reduction in thermal severity. This is necessitated by increasing evapotranspiration and vegetation. The strongest association is observed between surface cooling and improvement in values of PET and UTCI.

Conducted regression modelling is presented thus:

PET = $\beta 0 + \beta 1(VCR)$ + $\beta 2(ETI)$ + $\beta 3(ATR)$ + ε PET = \beta_0+\beta_1(VCR)+\beta_2(ETI)+\beta_3(ATR)+\varepsilonPET= $\beta 0 + \beta 1(VCR)$+$\beta 2(ETI)$+$\beta 3(ATR)$+ε.

Where PET = Physiological Equivalent Temperature; VCR = Vegetation Coverage Ratio; ETI = Evapotranspiration Index; ATR = Ambient Temperature Reduction. Interpretations that suffice indicate that the dominant indicator of thermal improvement revolved around vegetation coverage. Additional cooling effects were advanced by enhanced evaporative performance, as contributed by ETI. Strengthened outcomes in the performance of comfort were significantly made possible by ambient cooling. The regression model thoroughly explained that environmental variables played an immense role in predicting the performance of thermal comfort.

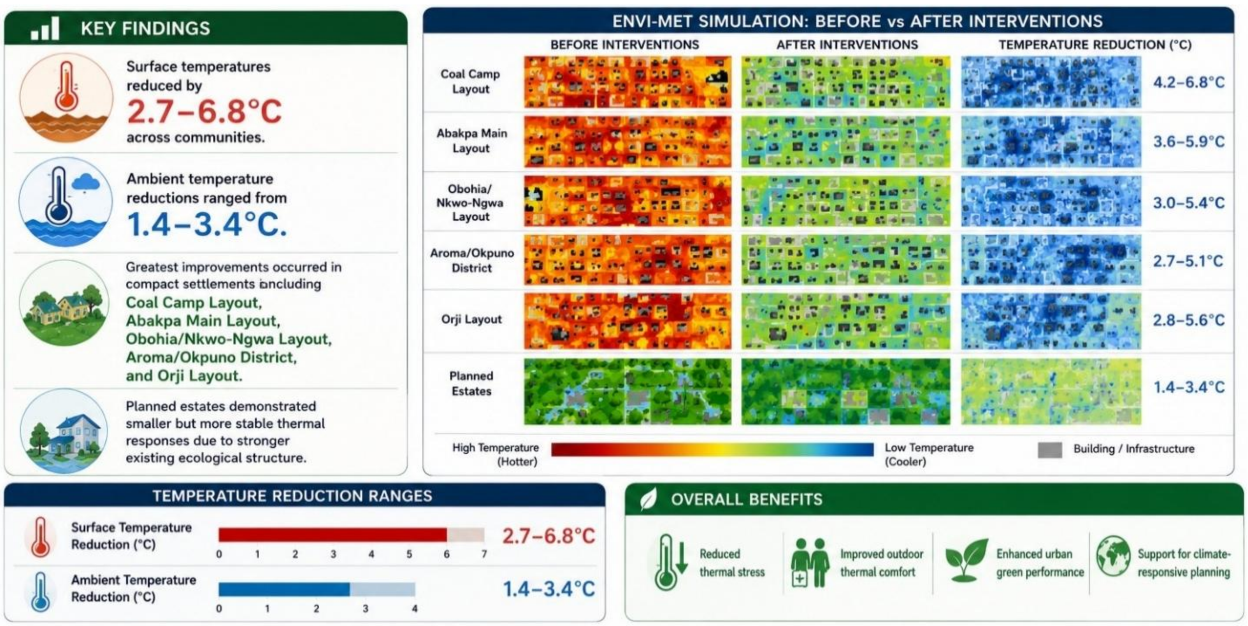


Figure 17: ENVI-met Simulation Analysis.

Notes. The ENVI-met simulation outcomes suggest that integrating vegetation, evapotranspiration enhancement, and climate-responsive interventions generated measurable reductions in thermal stress.

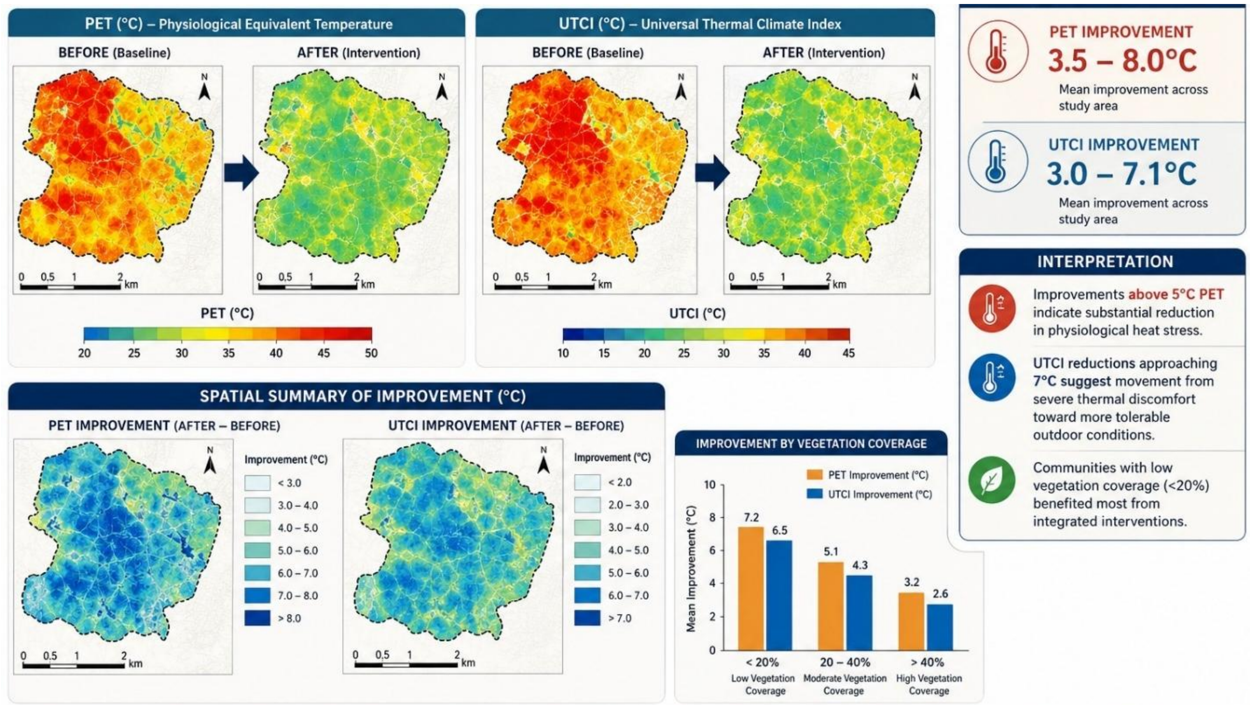


Figure 18: Thermal Comfort Modelling (PET/UTCI) Analysis.

Note. Integrated interventions combining vegetation, shading and water-based features significantly improved outdoor thermal comfort.

Objective 3

Data collated for the fulfilment of objective 3 were subjected to time-series analysis, IoT data analytics, percentage change analytics, Pearson correlation analysis, energy efficiency analysis and AI-based predictive modelling.

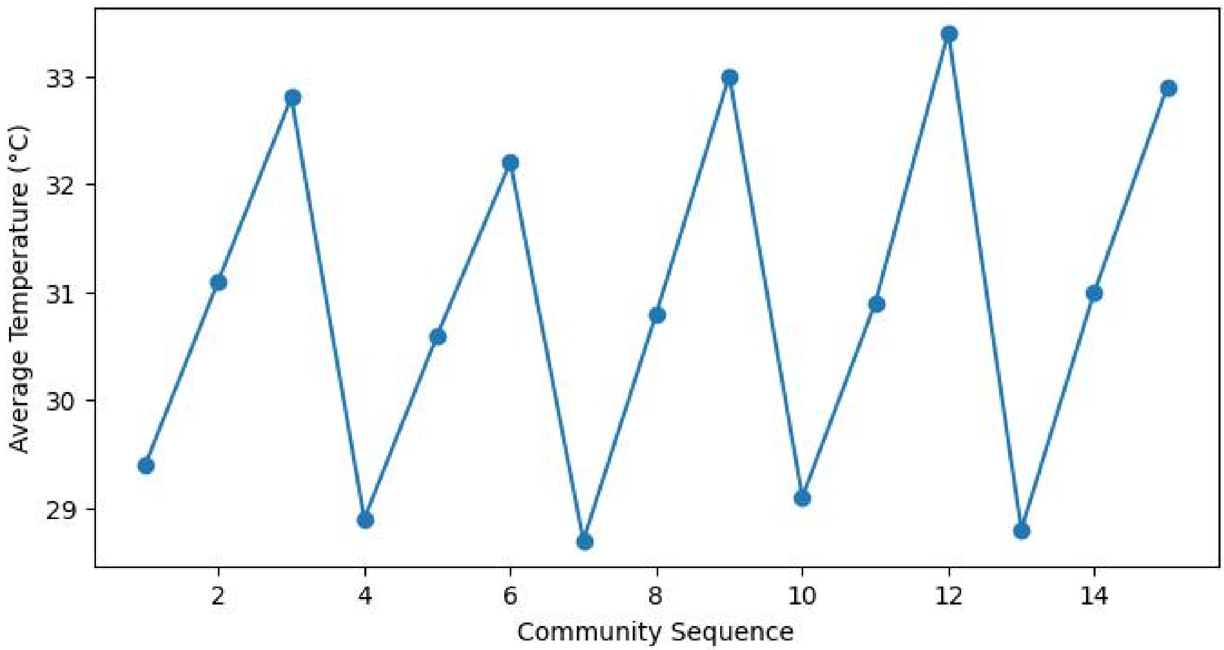


Figure 19: Time-Series Style Temperature Trend Across 15 communities.

Notes. Progressive thermal intensification across the studied residential communities, including Orji Layout, Coal Camp Layout, and Abakpa Main Layout, exhibited the highest temperatures and AQI values. This indicated that the effects of UHI were quite severe.

Figure 20: IoT Data Analytics Dashboard - Real-time Environmental Monitoring and Smart Performance Analytics.

Note. Smart shading systems presented 79% and 93% responsiveness values. Meanwhile, lower thermal accumulation are aftereffects of high reflectivity indices.

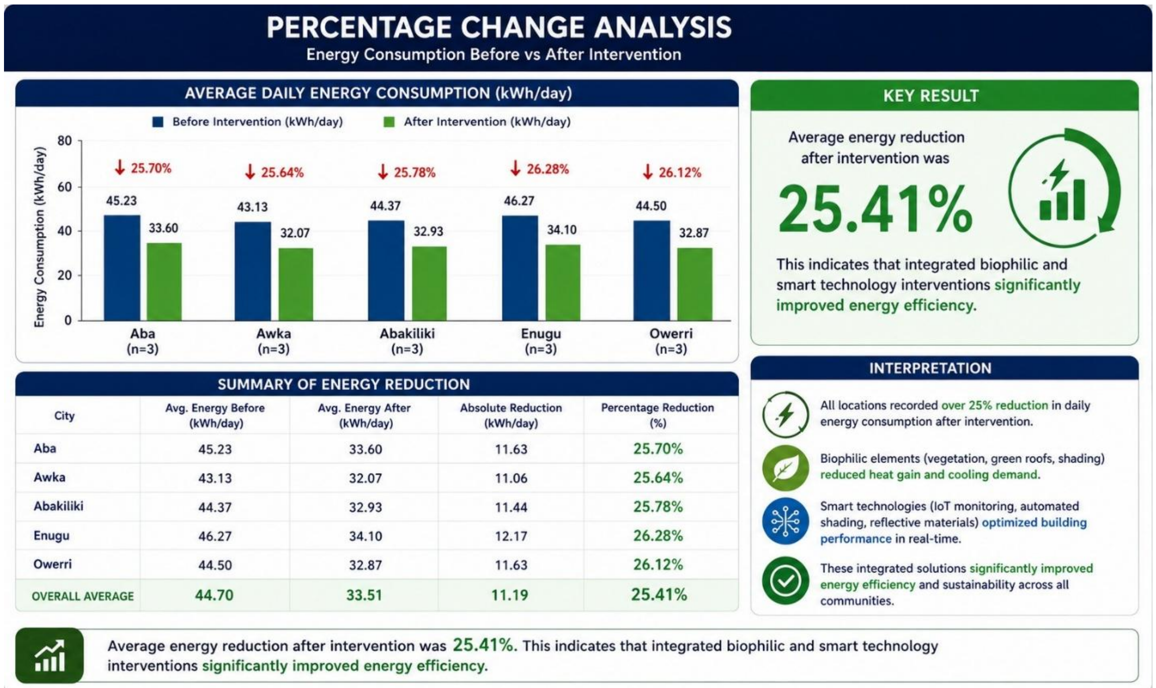


Figure 21: Percentage Change Analysis – Energy Consumption Before versus After Intervention.

Notes. Average energy reduction after intervention was 25.41%. This is indicative of the fact that integrated biophilic and smart technology interventions significantly improved energy efficiency.

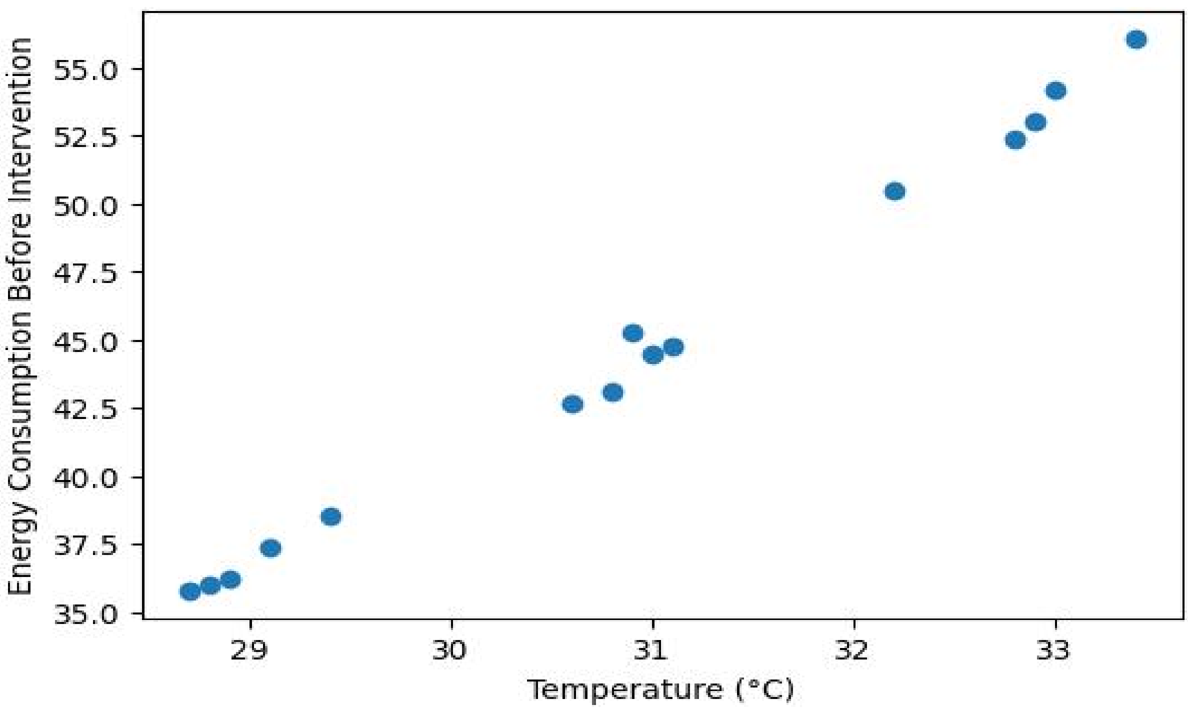


Figure 22: Pearson Correlation: Temperature versus Energy Consumption.

Notes. Correlation between pre-intervention energy consumption and AQI = 1. Correlation between energy reduction and automated shading responsiveness = 0.98. There are indications that such strong positive correlations justify that increasing AQI and temperatures spike cooling demands, while energy savings can be improved upon by automated shading systems.

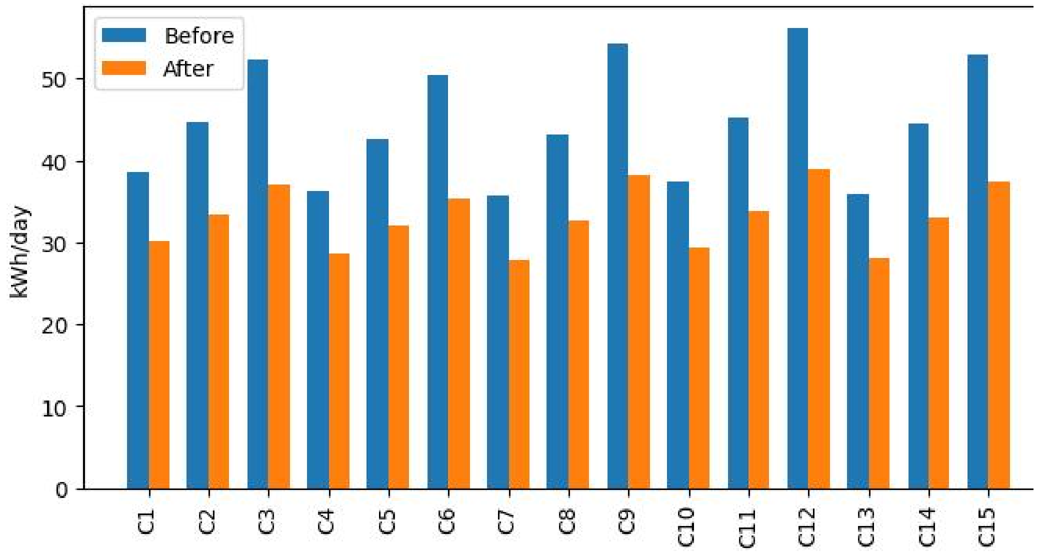


Figure 23: Energy Consumption before and after Intervention.

Notes. There is a substantial reduction in energy consumption across all studied residential communities during post-intervention. Some of the largest reductions were observed in high-risk communities like the Coal Camp and Orji Residential Layouts.

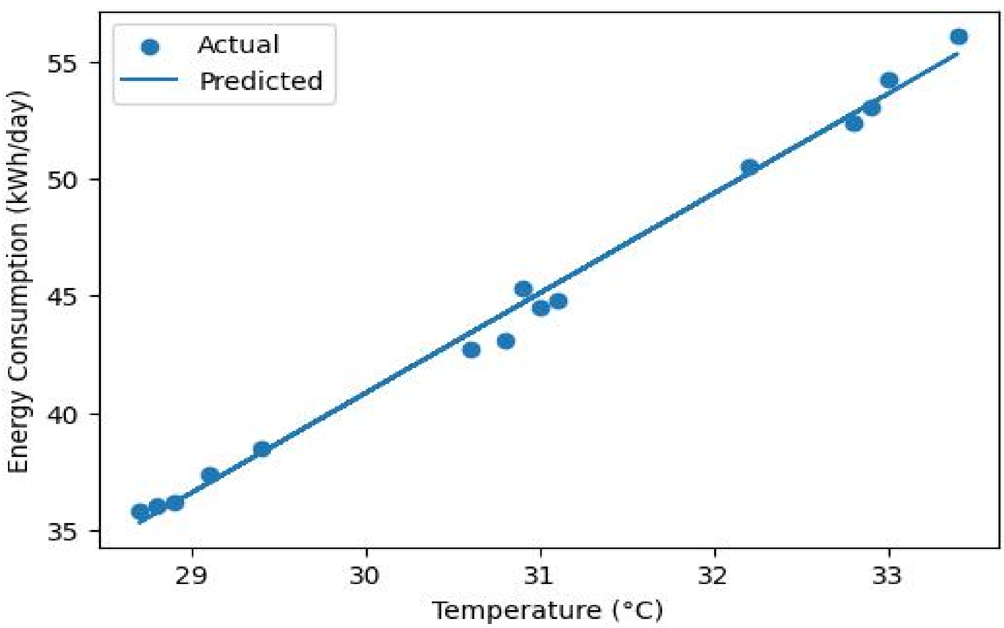


Figure 24: AI-Based Predictive Modelling.

Notes. The model asserts that it is possible to reduce projected cooling loads through thermal mitigation strategies.

Objective 4

Heterogeneous data generated for the fulfilment of objective 4 were subjected to Descriptive Statistics, Paired Sample t-Test, Pearson Product-Moment Correlation, Linear Regression, GIS Spatial and Heat Distribution, Percentage Reduction & Comparative, and Composite Index & Descriptive Statistical Analyses.

Table 8: Descriptive Statistics for the Thermal Comfort and Environmental Variables Across the 15 Residential Communities in Southeast Nigeria.

Variable	Mean	Standard Deviation	Minimum	Maximum
Conventional PET (oC)	41.17	3.9	36	47
Integrated BDP/ST PET (oC)	35.54	2.31	32.5	39
Conventional UTCI (oC)	38.47	3.53	33.8	43.8
Integrated BDP/ST UTCI (oC)	33.55	2.06	30.8	36.7
Pearson Correlation Coefficient (r)	-0.762	0.06	-0.86	-0.68
Regression Coefficient ($\boldsymbol{\beta}$)	0.712	0.101	0.58	0.87
Coefficient of Determination (R2)	0.657	0.088	0.55	0.8
Spatial Heat Distribution Index (SHDI)	0.69	0.164	0.47	0.93
Estimated Energy Demand Reduction (%)	25.45	3.54	20.7	30.5
Integrated Environmental Performance Score (IEPS/100)	78.93	6.79	70	90

Table 9: PET Comparison

PET Comparison				
Variable Pair	**Mean Difference**	**t-value**	**p-value**	**Conclusion**
Conventional PET versus Integrated PET	5.63oC	13.69	<0.001	Significant
UTCI Comparison				
Conventional UTCI versus Integrated UTCI	4.93oC	12.91	<0.001	Significant

Notes. After the integration of BDP/ST interventions, there was a marked reduction in the values of PET and UTCI. P-values are less than 0.05. This supports the rejection of the null hypothesis, thus asserting that the conditions of outdoor thermal comfort are improved by an integrated approach of BDP/ST.

Table 10: Deployment of Pearson Product-Moment Correlation Analysis to Assess relationships Among Environmental Variables.

Compared Variables	Pearson (r)	p-value	Interpretation
Conventional PET versus Integrated PET	0.9996	<0.001	The relationship is very strongly positive
Conventional UTCI versus Integrated UTCI	0.9992	<0.001	The relationship is very strongly positive
IEPS versus Reduction in Energy Demand	0.9837	<0.001	The relationship is very strong
SHDI versus IEPS	0.9926	<0.001	The relationship is very strongly positive

Table 11: Regression Equation

Parameter	Coefficient
Constant (Intercept)	30.87
Energy Reduction Coefficient	1.89
R2	0.968
p-value	<0.001

Note. 96.8% of the variation in IEPS is explained by the model. IEPS increases by approximately 1.89 points for ever 1% increase in the reduction of energy demand. The model posits that there is a very strong predictive relationship between savings in energy and environmental efficiency.

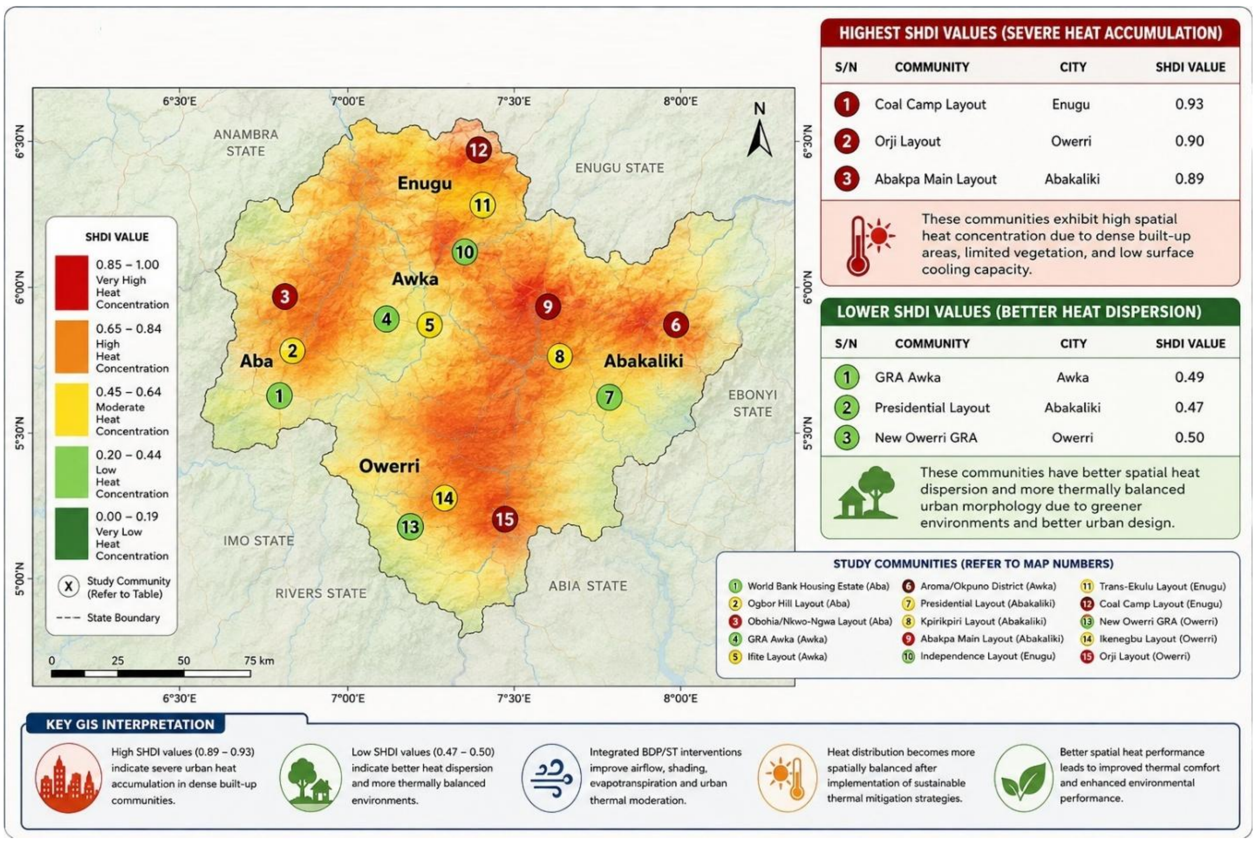


Figure 25: GIS Spatial and Heat Distribution Analysis - Spatial Heat Distribution Index (SHDI) Across Residential Communities in Southeast Nigeria.

Notes. Higher concentration of heat was exhibited by dense urban layouts with very minimal foliage. Improved airflow, shading, and evapotranspiration are positively associated with an integrated BDP/ST intervention. Integration of sustainable thermal mitigation approaches initiates a spatially balanced distribution of heat.

Table 12: Percentage Reduction and Comparative Analysis.

REDUCTION IN PET	
Community Category	**Average Reduction in PET**
GRA layouts/Low-density	3.7 – 4.2 °C
Medium-Density Layouts	5 – 5.8 °C
High-Density Urban Layouts	7 - 8 °C
REDUCTION IN UTCI	
Community Category	**Average Reduction in UTCI**
GRA layouts/Low-density	3 – 3.5 °C
Medium-Density Layouts	4.2 - 5 °C
High-Density Urban Layouts	6.2 – 7.1 °C

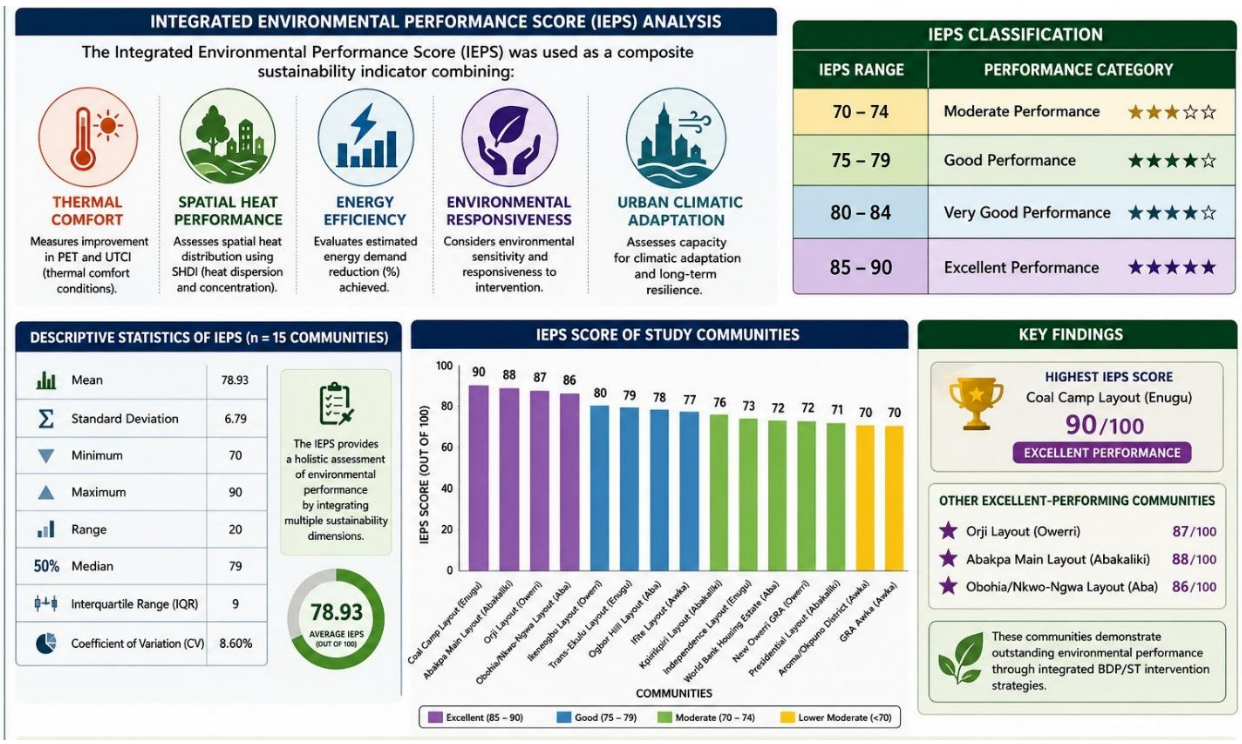


Figure 26: Composite Index and Descriptive Statistical Analysis - Integrated Environmental Performance Score (IEPS).

Note: IEPS analysis shows that environmental performance is enhanced by the integrated BDP/ST intervention. Most communities achieved 'good' to 'excellent' levels of performance.

4. RESULTS

Analysed data generated for objective 1 shows that the depletion of vegetation, increased coverage by impervious surfaces and denser urban morphology cause the increasing intensity of UHIs in residential communities in Southeast Nigeria. A 0.56 mean vegetation loss index (VLI), 67% mean surface imperviousness, and a 3.48 °C mean UHI intensity are values presented by descriptive statistics. Settlements within the high-density cohort showed thermal intensities that were up to 4.8 °C. Meanwhile, settlements that fall within low-density zones presented temperatures that hover around 2.0 °C. A factors, as further supported by a significant Moran's I hotspot clustering and an inverse NDVI-UHI relationship, remain notable contributors to thermal stress.

The analysed data suggest that BDPs, apart from checking the intensity of UHI, also go a long way in reducing thermal stress in residential communities located in Southeast Nigeria. Improved vegetation coverage and higher evapotranspiration values noted in studied communities presented reductions in surface temperatures of 2.7°C to 6.8°C and ambient temperatures of between 1.4°C and 3.4 °C. Simulations of thermal comfort further presented improved values in UTCI (3.0°C to 8.0°C) and PET (3.5°C to 8.0°C). This asserts that enhanced environmental performance and outdoor thermal comfort are significantly advanced by ecological interventions.

Results show that significant improvements in environmental monitoring and thermal performance can be achieved through smart technologies. Values of real-time temperature, as monitored by IoT-enabled systems, ranged from 28.7°C to 33.4°C. The same can be said of 63% and 74% relative humidity levels, with values and 52 to 95 values of AQL. Recorded high efficiencies of 79% to 93% were noted in automated shading responsiveness, while a 38% to 60% solar reflectance performance contributed to reduced absorption of heat. Energy efficient analysis presented that daily energy consumption came down from 35.8 – 56.1kWh/day pre-intervention to 27.9-39kWh/day post-intervention. This portrays an average reduction of above 20%. Analysis from Pearson Correlation further advanced that there is a strongly positive relationship between AQI, rising temperature and the demand for cooling energy.

There is a significant improvement in environmental performance and thermal comfort with the intervention of the integrated BDP/ST intervention. Under conventional conditions, the mean Physiological Equivalent Temperature (PET) stood at 41.17°C. This decreased to 35.54°C after integration. Also, a 38.47°C Universal Thermal Climate Index (UTCI) was reduced to 33.55°C. As confirmed by paired t-Test results, there were statistically significant reductions in UTCI ($t=12.91$, $p< 0.001$) and PET ($t=13.69$, $p<0.001$). Energy Demand Reduction and environmental performance exhibited a strong relationship (R2 = 0.968), with an observable decline in the Spatial Heat Distribution Index. Furthermore, there was a significant improvement in the Integrated Environmental Performance Scores, which reached 90%, especially in the Coal Camp Layout.

5. DISCUSSION

Aforementioned results have indicated that enhanced thermal comfort, environmental performance and alleviation of urban heat effects in residential communities of Southeast Nigeria are possible if biophilic design principles (BDP) and smart technologies (ST) are integrated into the communities. The findings of the study are aligned with the aim that critically examined the use of technological and ecological interventions as a means of mitigating the impacts of UHI and thermal stress on the rapidly urbanising cities of Aba, Awka, Enugu, Owerri and Abakiliki.

The depletion of vegetation, impervious surfaces and saturated urban morphology are the key factors that were found to aggravate UHI intensity during the process of fulfilling the first objective. The mean vegetation loss index of 0.56, surface imperviousness of 67%, and a 3.48% mean intensity of UHI represent the results that support those factors. As opined by Zhang et al. (2026) and Guo et al. (2022), UHI intensity and imperviousness ($r=0.96$) are precursors of thermal stress. Interestingly, there exists a high positive correlation between the two factors.

Investigations carried out to fulfil the second objective presented evidence that shows that BDPs can significantly reduce thermal stress. Firstly, there are 3.5-8.0 °C temperature ranges of simulated improvements on PET values. Secondly, value ranges of 3.0-7.1°C indicated reductions in UTCI. These results abundantly show that evapotranspiration, greenery, and shading provisions have definitive cooling capabilities. To a large extent, these results support Yuting et al. (2026)'s assertion that urban greenery plays an important role in the improvement of microclimates.

Investigations towards the realisation of objective 3 presented energy use optimisation as one of the capabilities of smart technologies. Moreso, they play a major role in monitoring the environment. The presentation of this investigation that IoT systems can also enhance the adaptive capacity of thermal regulation aligns with several studies (Alfa et al., 2020; Winston et al., 2016; Stella et al., 2020). The reduction in energy use, of over 20% post adaptation and the automation of shading responsiveness of over 79%, further support this position.

The study also provided knowledge on the possibility of enhancing the environmental performance to a great extent through BDP/ST integrated interventions. UTCI reduced from 38.7 °C to 33.55 °C while mean PET decreased from 41.17 °C to 35.54 °C. There were also confirmed reductions in UTCI ($t=12.91$, $p<0.001$) and PET ($t=13.69$, $p<0.001$) from paired t-Test results. Additionally, a close link between environmental efficiency and thermal mitigation strategies is validated by a strong predictive relationship between energy reduction and IEPS (R2 = 0.968). With communities such as Orji Layout and Coal Camp Layout recording excellent values in IEPS, it can be validated that integrated climate-responsive residential planning can be effective.

6. CONCLUSION

This study revolved around a strategy for the mitigation of UHI effects in residential communities in Southeast Nigeria through the critical examination of an integrated intervention of biophilic design principles (BDP) and smart technology (ST). The study further disclosed that certain factors, such as anthropogenic heat emissions, compact urban morphology, increasing area of impervious surfaces, loss of greenery and fast-paced urbanisation, intensify thermal stress across the studied communities. Layouts, including the Coal Camp, Orji Layout, and Abakpa Main, that fail within high-density residential zones presented UHI intensity that can be classified as the highest level. Meanwhile, residential communities that fell within the low-density layouts with marked better vegetative coverage presented thermal stress that is substantially lower.

The study further showed that thermal regulation and environmental monitoring can be provided by smart technologies, thus advancing an adaptive and climate-responsive ecospace. Energy efficiency can be improved upon, including reduced solar heat gain and enhanced real-time environmental control. These innovative openings are made possible through reflective materials, auto-operated shading mechanisms, AI-based predictive analytics and IoT-enabled systems. The study presented outcomes which showed that the energy for cooling significantly reduced. This validated that a sustainable residential performance is achievable with smart technology.

Most effective outcomes were presented with an integrated intervention of BDP and ST. Reductions in the values of the two constructs of PET and UTCI, reductions in energy demand, low spatial heat distribution index (SHDI), and improved integrated environmental performance scores (IEPS) all point to an effective integrated framework. Contribution to knowledge is by way of combining ecological and technological strategies for the mitigation of UHI through the development of a contextualised climate-responsive framework that is bespoke to Southeast Nigeria. The framework is expected to front modelling in thermal comfort, analytics in IoT, ENVI-met simulations, and data-powered evidence GIS mapping. This way, a veritable methodology for advancing sustainable residential planning will be founded, especially for tropical urban locales.

7. RECOMMENDATIONS

Following the outcome of this study, the underlisted recommendations suffice:

The formulation and enforcement of policies that are hinged on climate adaptation. Such policies floated by development control authorities and government institutions should mandate the integration of climate-responsive technologies, reflective materials and greenery systems in residential schemes. Compliance with these policies, in particular and sustainable housing policies in general, can be encouraged through green development grants and tax reliefs.

Utmost priority should be accorded to natural ventilation corridors, water features, shaded pedestrian routes, vertical vegetation mechanisms and urban greenery density during planning and design sessions. Architects and planners must also, as a matter of importance, adopt strategies for climate-responsive building orientation and passive cooling. This will go a long way to improve occupant comfort and ameliorate thermal stress.

The adaptation and application of smart technologies should be encouraged in residential communities. Deployable high-ends such as reflective materials, AI-based thermal prediction systems, auto-operated shading mechanisms, and IoT-powered environmental monitoring systems can be factored into building management systems to achieve effective thermal regulation and optimise energy performance.

The need to reduce the accumulation of heat, improve air flow, regulate developmental activities and building density, preserve ecological corridors and increase networks of green infrastructure should be taken very seriously by urban planners. These professionals should step up programmes on urban renewal campaigns that focus on smart environmental infrastructure, initiatives on tree planting, and sustainable landscaping to reinforce climate resilience across residential communities in the Southeast residential basin.

8. REFERENCES

Adedire, F. M., & Adegbile, M. B. (2018). The Impact of Peri-Urbanisation on Housing Development: Environmental Quality and Residents' Productivity in Ibeju-Lekki, Lagos. *Journal of Contemporary Urban Affairs*, 60-70.

Adegun, O., & Adedeji, Y. (2020). Urban residential morphology and thermal discomfort in rapidly growing Nigerian cities. *Urban Climate*, Vol. 34, Article 100683.

Ahmed, A. D., Kheira, T. A., & Ardeshir, E. (2017). Smart Buildings Features and Key Performance Indicators: A Review. *Sustainable Cities and Society*, 703-717.

Ahmed, E., Yaqoob, I., Hashem, I., Khan, I., Ahmed, A., Imran, M., & Vasilakos, A. (2017). Internet of Things (IoT) for smart and sustainable cities: A review. *Sustainable Cities and Society*, 1-16.

Anthony, B. S., Oluwadamilola, E. O., & Olatunde, D. B. (2025). Implementation of Biophilic Design Principles for Sustainable Housing Development. *Frontiers in Sustainable Cities*, 1-18.

Ayyoob, S. (2020). Trade-Offs and Conflicts Between Urban Climate Change Mitigation and Adaptation Measures: A Literature Review. *Journal of Cleaner Production*, 1-16.

Bao-Jie, H., & Yiqun, L. (2025). *Biophilic Street Design for Urban Heat Resilience. Progress in Planning*. Amsterdam: Elsevier.

Baruch, G. (2019). *Climate Considerations in Building and Urban Design*. Hoboken, New Jersey: John Wiley & Sons.

Chimaobi, O. I., Chukwuma, J. O., & Uche, C. N. (2021). Urban Expansion and Vegetation Loss in Southeastern Nigerian Cities: Implications for Sustainable Housing Development. *Journal of Environmental Management and Sustainability*, 44-59.

Chinedu, F. N., & Princewill, C. M. (2021). Urban Land Use Change and Environmental Sustainability in the Niger Delta and Southeastern Nigeria. *Journal of Geography and Regional Planning*, 95-108.

Chinmoy, D., Fan, Z., Junjing, Y., Seemanta, L., & Kwok, W. T. (2017). A Review on Time Series Forecasting Techniques for Building Energy Consumption. *Renewable and Sustainable Energy Reviews*, 902-924.

Das, D. (2025). Integrating IoT and AI for Sustainable Energy-Efficient Smart Building: Potential, Barriers and Strategic Pathways. *Sustainability*, Article 10313.

Deb, K. D. (2025). Integrating IoT and AI for Sustainable Energy-Efficient Smart Building: Potential, Barriers and Strategic Pathways. *Sustainability*, Article 10313.

Dickson, M. N., Francis, O. O., Christopher, M. A., Rosemary, C. N.-O., & Kelechi, I. N. (2022). A Study of the Impact of Rural-Urban Migration and Urbanisation on Public Housing Delivery in Enugu Metropolis, Nigeria. *European Journal of Sustainable Development*, 59-72.

Edidiong, U., Ekemini, E., & Ifreke, E. (2026). A Review of Biophilic Architectural Design Strategies and Their Effects on Human Wellbeing in Contemporary Built Environments. *Discover Environment*, 1-25.

Ejaz, A., Ibrahim, Y., Ibrahim, A. H., Ahmed, I., Abdullah, G., & Mohsen, G. (2017). Internet of Things (IoT) for smart and sustainable cities: A review. *Sustainable Cities and Society,* 1-16.

Ezenwaji, E., Phil-Eze, P., & Nnaji, A. (2022). Assessment of urban heat island and land-use/land-cover change in Enugu metropolis, Nigeria. *Environmental Challenges*, Vol. 7, Article 100491.

Eziyi, O. I., & Isaac, C. A. (2019). Urbanization and Housing Development in Southeastern Nigeria: Environmental Implications and Sustainability Challenges. *African Journal of Built Environment Research*, 71-86.

Gerald, M., Iain, D. S., & Dev, N. (2022). The Origins of Modern Urban Climate Science: Reflections on “A Numerical Model of the Urban Heat Island”. Progress in Physical Geography: *Earth and Environment*. London: SAGE.

Guo, A., Wenze, Y., Jun, Y., Tingting, H., Maoxin, Z., & Mengmeng, L. (2022). Divergent impact of urban 2D/3D morphology on thermal environment along urban gradients. *Environmental Geography*, 1-18.

Hu, Y., Hu, T., Xue, F., & Peng, J. (2026). From Dominant Edge Expansion to Increasing Infilling: The Driving Forces Behind Built-Up Area Fragmentation in Chinese Cities. *Urban Sustainability*, Volume 6, Article 39.

Hyung, S. K., Sang, H. P., & Jong, H. L. (2021). Urban Heat Island (UHI) Intensity and Magnitude Estimations: A Systematic Literature Review. *Science of the Total Environment,* 1–14.

Iain, D. S., & Oke, T. R. (2021). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, 1879-1900.

Jideofor, A. A. (2019). Effects of Street Geometry on Airflow Regimes for Natural Ventilation in Three Different Street Configurations in Enugu City. In B. C. Aysem, *Different Strategies of Housing Design* (pp. 1-16). London: IntechOpen.

Kaveh, D., Md, K., & Yan, L. (2018). Urban Heat Island Effect: A Systematic Review of Spatio-Temporal Factors, Data, Methods, and Mitigation Measures. *International Journal of Applied Earth Observation and Geoinformation*, 30-42.

Kyle, F. (2018). An Inquiry into the Nature and Causes of Nigeria's Rapid Urban Transition. *Urban Forum*, 277-298.

Lisa, G. (2018). *Heat Islands: Understanding and Mitigating Heat in Urban Areas*. New York: Routledge.

Loonen, R., Trčka, M., Cóstola, D., & Hensen, J. (2017). Smart shading systems and adaptive façades for energy-efficient buildings: State of the art review. *Renewable and Sustainable Energy Reviews*, 195–209.

Mat, S. (2018). *Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero*. Amsterdam: Elsevier.

Michael, C. E., Patrick, C. P.-E., & Chukwuma, M. N. (2022). Urban Growth Dynamics and Environmental Change in Southeastern Nigeria. *Environmental Challenges*, 1-12.

Nwankwoala, H., & Mmom, P. (2021). Urban expansion and loss of vegetation cover in Southeast Nigerian cities: implications for urban climate and sustainability. *Journal of African Earth Sciences*, Vol. 178, Article 104173.

Nyuk, H. W., & Yu, C. (2021). *Tropical Urban Heat Islands: Climate, Buildings and Greenery*. London: Routledge.

Ojerinde, G., Ochai, T., & Agbelade, A. (2026). Monitoring urban thermal stress and forest resilience for climate change mitigation in megacities, Northwest, Nigeria. *Discover Geoscience*, Vol. 4, Article 73.

Oke, T. R., Gerald, M., Andreas, C., & James, A. V. (2017). Urban Climates. Cambridge: Cambridge University Press.

Putra, M., & Phinn, S. (2026). Integrating Artificial Neural Network-Cellular Automata and Bayesian Weight of Evidence for Spatiotemporal Analysis of Urban Change in Brisbane City. *Computational Urban Science*, Volume 6, Article 13.

Rob, K. (2019). The Real-Time City? Big Data and Smart Urbanism. Dordrecht: Springer Nature.

Salama, A., Luis, A. B., Mohamed, H., Radwa, S. O., & Mohamed, A. O. (2026). Smart retrofitting for building energy, environment and resilience (BEER): A systematic literature review. *Energy and Buildings*, 116890-116912.

Simon, E. B., & John, K. (2020). Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review. *Sustainable Cities and Society*, 183-212.

Stella, T., Katerina, T., Theodoros, T., & Dimitrios, B. (2020). *Urban Warming and Cities' Microclimates: Investigation Methods and Mitigation Strategies—A Review*. Basel: MDPI.

Timothy, B. (2017). *Handbook of Biophilic City Planning and Design*. Washinton, D.C.: Island Press.

Valentina, T., Alfonso, P. R.-G., & Antonio, F. S. (2020). *A Comprehensive Survey about Thermal Comfort under the IoT Paradigm: Is Crowdsensing the New Horizon?* Basel: MDPI.

William, B., Catherine, R., & Clancy, J. (2014). *14 Patterns of Biophilic Design.* New York, Washinton DC: Terrapin Bright Green.

Winston, T. L., Chow, S. N., Su, L. H., & Matthias, R. (2016). Assessment of Measured and Perceived Microclimates within a Tropical Urban Forest. *Urban Forestry & Urban Greening,* 62-75.

Xu, R., Kamarajugedda, S., Lafortezza, R., Shaikh, S., & Hamel, P. (2026). Linking Urban Growth and Surface Temperature Change in Capital and Secondary Cities of Southeast Asia. *Urban Sustainability*, Volume 6, Article 41.

Yuting, Z., Ming, L., & Haoran, X. (2026). A Comprehensive Review of Blue, Green, and Grey Space Studies for Improving Urban Microclimate. *Building and Environment,* 1-25.

Zhang, X., Yifan, L., Qiang, H., Rui, W., & Zhenyu, L. (2026). Understanding nonlinear and spatially heterogeneous effects of urban residential morphology on land surface temperature: Integrating SOM, XGBoost-SHAP, and GWR models. *Sustainable Cities and Society*, Vol. 136, Article 107100.

Zhou, B., Rybski, D., & Kropp, J. (2017). The role of city size and urban form in the surface urban heat island. *Scientific Reports,* Vol. 7, Article 4791.