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Spatiotemporal characteristics of population density, heat stress vulnerability, and effects of urban green spaces in Lagos, Nigeria

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Abstract

Rapid urbanization in Lagos, Nigeria, has intensified population density and altered local microclimates, exposing residents to increased risks of heat stress. As one of Africa's largest megacities, Lagos faces challenges in balancing urban growth with environmental sustainability. This study investigates the spatiotemporal characteristics of heat stress vulnerability and the moderating effects of urban green spaces (UGSs) across 11 local government areas (LGAs) in Lagos, Nigeria. Land surface temperature (LST) for 2013, derived from Landsat 8 Operational Land Imager imagery, was analyzed alongside 2013 population statistics and household questionnaire data collected from residents nearest to 15 observation sites. Each LGA was represented as a polygon feature in ArcGIS. Exposure indicators included LST, population density, and LST hotspot clusters; sensitivity indicators included vulnerable age groups (0–4 and 65+ years), low educational attainment, and income classes; and adaptive-capacity indicators included ownership of air conditioners and fans, proximity to water bodies, and proximity to grass or green spaces. Results reveal five population density categories across the metropolis. Yaba exhibits extremely high density (93,320–339,100 persons/km^2), while areas such as Abule-Egba, Mushin, Ilupeju, and Shomolu fall within high to moderately high density ranges. LST hotspot analysis indicates that Amuwo-Odofin, Isolo, Yaba, Ilupeju, Shomolu, Alagbado, and Ikotun are statistically significant hotspot locations at the 95–99% confidence level. Conversely, Oko-Afo, Ajangbadi, City Hall, Marina market, and Abule-Egba were not classified as hotspots due to inherent adaptive capacities, while Oshodi and Ejigbo emerged as cold spots. Adaptation measures vary across the metropolis. Ownership of air conditioners and fans, along with proximity to vegetation and water bodies, were the dominant strategies for mitigating heat exposure. The study underscores the critical role of UGSs in reducing heat stress vulnerability and highlights the need for strategic urban planning interventions to enhance adaptive capacity in Lagos.

Keywords: Heat stress; Urban green space; Population density; Land surface temperature; Vulnerability; Lagos

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1. Introduction

Urban green spaces (UGSs) are declining globally due to rapid urbanization, increasing population density, and continuous spatial expansion. Lagos, like many large cities, has experienced a major reduction in vegetated areas as built-up areas replace natural land cover. This trend contributes to higher city temperatures and intensifies the urban heat island (UHI) effect, a phenomenon widely documented across different climatic regions.[1] Rising temperatures in cities have been directly linked to the loss of UGSs, which play important roles in regulating local climates, improving air quality, supporting recreation, maintaining hydrological balance, reducing pollution, promoting social interaction, and enhancing the overall quality of urban life.[2]

Several foundational studies have established strong relationships between urban population characteristics and the development of UHI conditions. Oke's[3] early work demonstrated that UHI intensity decreases with higher regional wind speed and increases with city population size.[3] Later studies by Jauregui,[4] Hogan and Ferrick,[5] Montavez *et al.*,[6] and Smith and Levermore[7] also found that expanding cities with dense built surfaces and increased human-generated heat tend to exhibit greater UHI intensities. Debbage and Shepherd[8] showed that both compact high-density areas and sprawling urban layouts can intensify UHI conditions, while Steeneveld *et al.*[9] confirmed strong correlations between population density and extreme UHI events in European cities.

The combined influence of climate change, rapid urban growth, and demographic pressure has increased heat exposure risks in many tropical cities. In Lagos, where temperatures remain high year-round, residents who cannot afford cooling technologies, such as air conditioners, are highly vulnerable to heat stress.[10] High temperatures have direct effects on public health by increasing heat-related illness and physiological strain. Medical experts warn that extreme heat in Lagos may worsen the spread and severity of climate-sensitive diseases, including Lassa fever, meningitis, and cholera, as well as other infectious outbreaks.[11] The World Health Organization also notes that rapid demographic and environmental changes, together with climate change, are increasing the frequency and severity of infectious disease events around the world.[12]

Despite the pressures from urban growth, UGSs remain essential for improving thermal comfort within cities. Vegetation cools the environment through shading and evapotranspiration, reducing the amount of heat absorbed and re-emitted by built surfaces. Numerous studies have confirmed that UGSs and blue infrastructure, such as tree cover, parks, and water bodies, can reduce heat stress and lower heat-related mortality in cities.[13] Their importance is especially clear in fast-growing cities like Lagos, where built surfaces dominate, and green space scarcity increases heat accumulation.

Concerns about persistent extreme heat in Lagos highlight the need to understand how different populations experience heat risk and how UGSs can reduce that risk. The vulnerability framework used in this study, encompassing exposure, sensitivity, and adaptive capacity, provides a comprehensive approach to assessing how heat impacts diverse communities.[14] By combining satellite-based land surface temperature (LST), demographic information, and data on household adaptation practices, this study explores the spatial pattern of heat stress vulnerability in Lagos and emphasizes the value of green infrastructure in building environmental resilience.

Mitigating the impacts of the urban climate, especially the UHI effect, requires deliberate planning strategies that moderate thermal conditions within built environments. One of the most effective approaches is integrating urban greening initiatives, including planting trees and other vegetation, implementing green roofs and cool roofs, and using reflective paving materials on streets and sidewalks. These interventions help regulate surface temperature, reduce heat storage in buildings, and enhance overall comfort within cities.[15]

Public parks and private green areas surrounding residential and commercial buildings significantly contribute to the quality of urban environments. They help reduce surface and air temperatures, improve thermal comfort, and promote various ecological benefits. Studies have long recognized that even a single tree can contribute to localize cooling, although the effect is limited to a small area.[16] In contrast, large urban parks can influence thermal conditions beyond their boundaries and create cooler microclimates in the surrounding built-up areas. Vegetation does not always cool the air directly, but it moderates temperatures by shading surfaces and reducing the rate of heating.[2]

A growing body of research emphasizes that natural elements, such as parks, forests, tree belts, and water bodies, enhance the livability of cities. These features provide environmental benefits, including water purification, air filtration, noise reduction, and local climate stabilization. They also support social and psychological well-being by offering spaces for recreation and social interaction.[17] However, without strategic design, maintenance, and management, urban parks may become underutilized or poorly maintained. Recent studies indicate that the value of green spaces is contingent on their effective integration into broader urban sustainability goals, particularly in rapidly growing cities.[18]

In rural landscapes dominated by vegetation, cooling occurs primarily through shading and evapotranspiration, which transfers moisture from the surface to the atmosphere.[19] Urban environments, however, are dominated by impervious materials, such as asphalt, concrete, and metal surfaces that absorb large amounts of heat during the day and release it at night. As cities expand and vegetation is cleared, reduced surface moisture limits the capacity for evaporative cooling. This contributes to higher daytime temperatures and persistent nighttime heat, intensifying both surface and atmospheric heat islands.[19]

Areas with extensive impervious cover, sometimes exceeding 75%, experience lower natural cooling than vegetated areas where impervious surfaces account for <10%.[20] To counter this, researchers have proposed several mitigation measures, including roof ponds, evaporative cooling systems, water features, and increased vegetation cover around residential and commercial structures.[21] Urban form also plays a crucial role; the orientation and geometry of buildings influence solar access and heat retention, making building design an important consideration in reducing urban heat.[22]

Vegetation reduces ambient temperatures by shading surfaces and through evapotranspiration, which converts incoming solar radiation into latent heat rather than sensible heat. The cooler surfaces then emit less long-wave radiation, reducing human exposure to heat.[23] The type, density, and spatial arrangement of vegetation near buildings can greatly influence indoor and outdoor temperatures, as well as energy demand for cooling. In dense subtropical cities, vegetation has been shown to reduce heat accumulation in buildings by more than 30%.[23]

Recent studies also highlight the role of urban morphology in determining when and how cooling can occur. For example, some cities experience morning cool islands where urban areas are temporarily cooler than surrounding rural areas. This effect depends largely on building configuration, vegetation cover, and human-generated heat.[24] In Lagos, where rapid urban growth has altered the landscape and reduced green cover, understanding these dynamics is essential for developing climate-resilient urban planning strategies.

2. Materials and methods

2.1. Study area

Lagos is the smallest state in Nigeria by land area, but it remains the most urbanized and industrialized part of the country. It ranks among the largest and fastest-growing metropolitan regions in the world, and it is currently the most populous urban center in sub-Saharan Africa. The state comprises 20 local government areas (LGAs), of which 16 form the densely populated metropolitan core.[25] Geographically, Lagos lies between longitudes 2°42' and 3°42' east and latitudes 6°22' and 6°42' north, occupying a coastal zone that contains a network of lagoons, creeks, barrier spits, and extensive wetlands (Figure 1).[26]

Population growth in Lagos is rapid. The population rose from 345,137 in 1952 to more than a million in 1963, over 5 million in 1988, and 9.1 million in 2006, according to census data.[27] Recent estimates suggest that the population to be 17,156,400 in 2025, with a 3.2% annual growth rate compared to 2.6% national population growth rate.[28,29] This sustained expansion has made Lagos one of the most rapidly growing cities in the world and a major destination for internal migration. Lagos serves as an economic and cultural hub, drawing residents from more than 250 ethnic groups in Nigeria.

According to recent urban area assessments, Lagos covers approximately 1,425 km^2, with a population density estimated at about 9,000 persons/km.[28,29] The city consumes more than half of Nigeria's electricity generation and accommodates over half of the country's vehicles, all concentrated within an already stressed road network. Nearly 80% of the population resides on just 37% of the land area. Economic activities, administrative functions, and commercial services are heavily concentrated within this metropolitan zone.

2.2. Climate and vegetation

Lagos experiences a wet equatorial climate influenced by its coastal location near the Gulf of Guinea and its proximity to the equator. The region features deep, poorly drained soils, and is characterized by a complex drainage network comprising lagoons, wetlands, and waterways that account for nearly one-quarter of the total land area.[29] Major water bodies include the Lagos and Lekki lagoons, the Ogun and Yewa rivers, and several creeks, such as the Ologe, Kuramo, and Five Cowries creeks. Combined, these water bodies and wetlands cover more than 40% of the state's area, and about 12% of the land is prone to seasonal flooding.[29]

Temperatures in Lagos remain high throughout the year. The mean annual temperature is about 28°C, with average maximum and minimum temperatures of 33°C and 26°C, respectively. Rainfall is substantial from May to November, though monthly variations in peak values are significant.[29] This combination of high temperature and high humidity increases the likelihood of urban heat discomfort and heat stress.

2.3. Methods

This study developed a heat-stress vulnerability index for Lagos by combining three components: exposure, sensitivity, and adaptive capacity. These components were used to assess how population characteristics, thermal

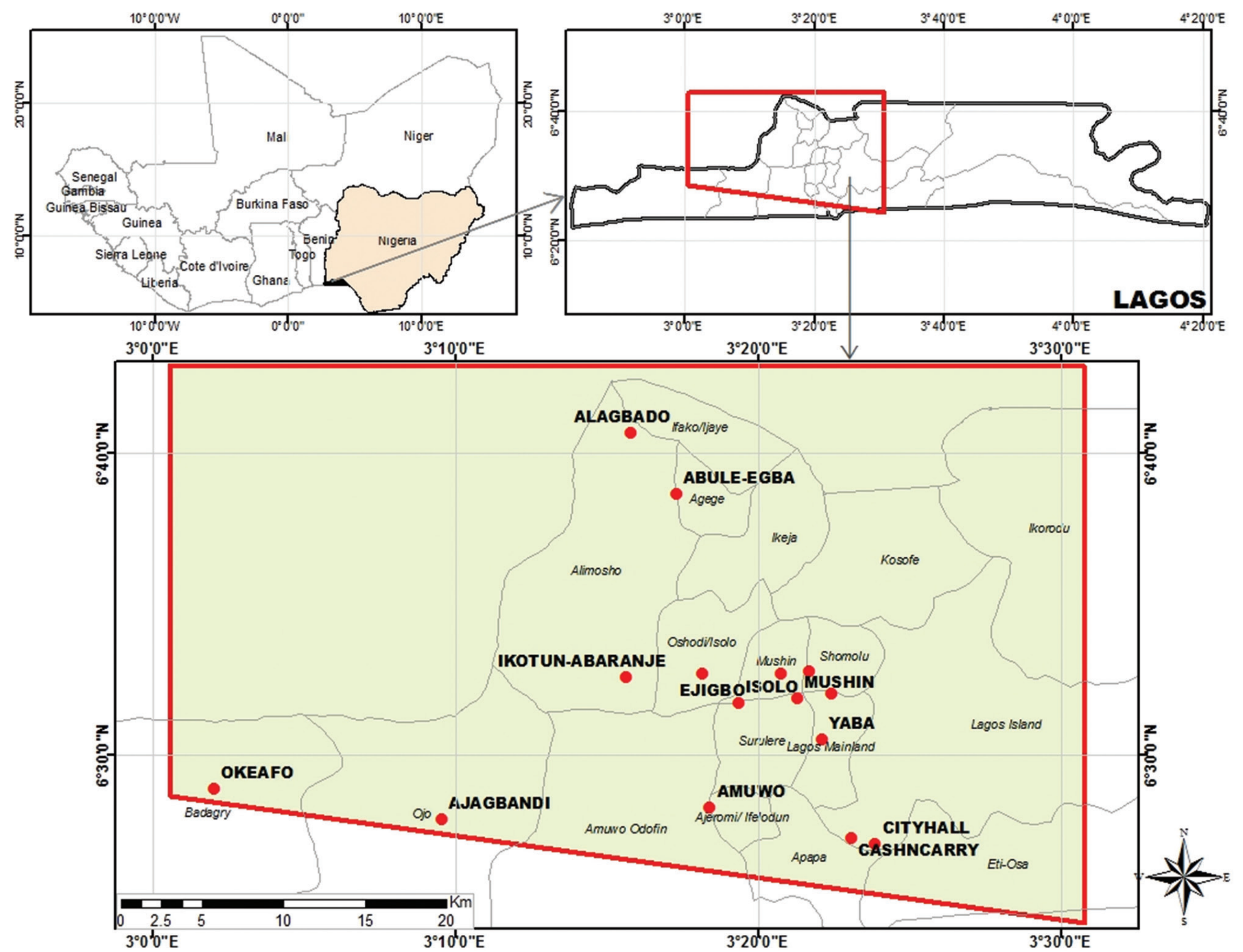

Figure 1. Map of the study area showing the locations of the study sites

conditions, and local environmental features influence vulnerability across different LGAs. The vulnerability framework employed in this study followed the exposure–sensitivity–adaptive capacity structure widely used in Intergovernmental Panel on Climate Change assessments and in several heat vulnerability index studies. Indicators were selected based on conceptual relevance and data availability within the Lagos context. Variables such as population density, age group, vegetation cover, and access to cooling devices have also been used in similar studies globally to represent components of heat exposure, sensitivity, and adaptative capacity. While several indicators, such as ownership of fans or air conditioners, function as proxies rather than complete measures of adaptive capacity, they reflect locally meaningful variations in a household's ability to regulate indoor temperatures. The conceptual framework is summarized in Figure 2.

LST data for 2013 were obtained from Landsat 8 Operational Land Imager imagery (metadata are provided in Appendix). Population data for the 11 LGAs included in the analysis (Alagbado, Abule-Egba, Ikotun, Isolo, Oshodi, Mushin, Shomolu, Yaba, Amuwo-Odofin, Ajangbadi and Oko-afo) were based on projections from 2013. Each LGA was represented as a polygon within ArcGIS (version 10.2, Environmental Systems Research Institute, United States of America), and spatial analysis incorporated population density, LST values, and cluster hotspot detection (Figure 3). In addition, questionnaires were administered to 200 households located near the 15 temperature observation sites across the 11 LGAs. These surveys provided information on exposure factors, sensitivity indicators, and adaptation practices. The remaining nine LGAs without temperature observation sites were classified as "no data" areas. A multi-stage purposive sampling procedure was employed to select respondents for the household survey. The 200 households were drawn from communities located within the vicinity of the 15 temperature observation sites distributed across the 11 LGAs with available thermal and demographic data. This exploratory sampling frame allowed the study to capture adaptation behaviors and household-level characteristics that spatially correspond to measured LST patterns. The sample was therefore not intended to be statistically representative of the entire Lagos population, but rather to provide contextual insights into household-level sensitivity and adaptive capacity in areas experiencing varying heat conditions.

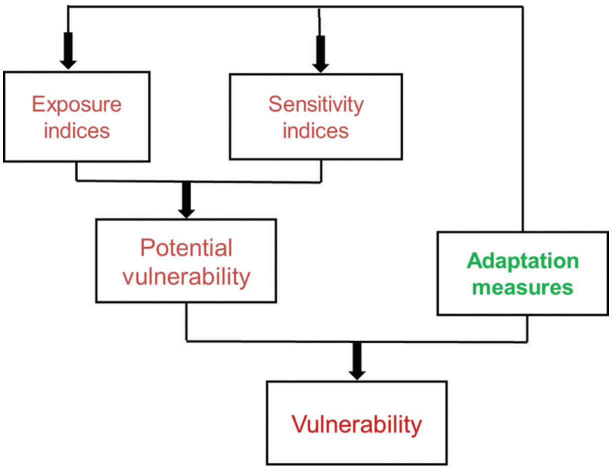

Figure 2. Conceptual model for heat stress vulnerability (adapted from Schroeter *et al.*[30] and Ebi *et al.*[31])

Adaptation strategies considered in the analysis included ownership of air conditioners and fans, proximity to vegetation or green spaces, and proximity to water bodies, such as open water or swimming pools. Adaptation capacity was grouped into three categories:

(i) High adaptation: Households that primarily rely on air conditioners and any other adaptation method
(ii) Medium adaptation: Households that rely mainly on fans and at least one additional strategy other than air conditioning
(iii) Low adaptation: Households that rely on any adaptation strategy but fall below the mean values for both air conditioner and fan ownership.

These adaptation measures, combined with exposure and sensitivity indicators, formed the basis for constructing the heat vulnerability index for Lagos. The analysis relied on 2013 Landsat LST data and 2013 population estimates because these were the only harmonized datasets that aligned with the period of the original household survey and were spatially complete for the 11 LGAs included in the study. At the time of analysis, recent LST and population datasets lacked full spatial coverage or consistent methodological processing across all LGAs, which would have introduced temporal or spatial inconsistencies into the vulnerability assessment. Therefore, the results should be interpreted as a 2013 baseline of urban heat exposure

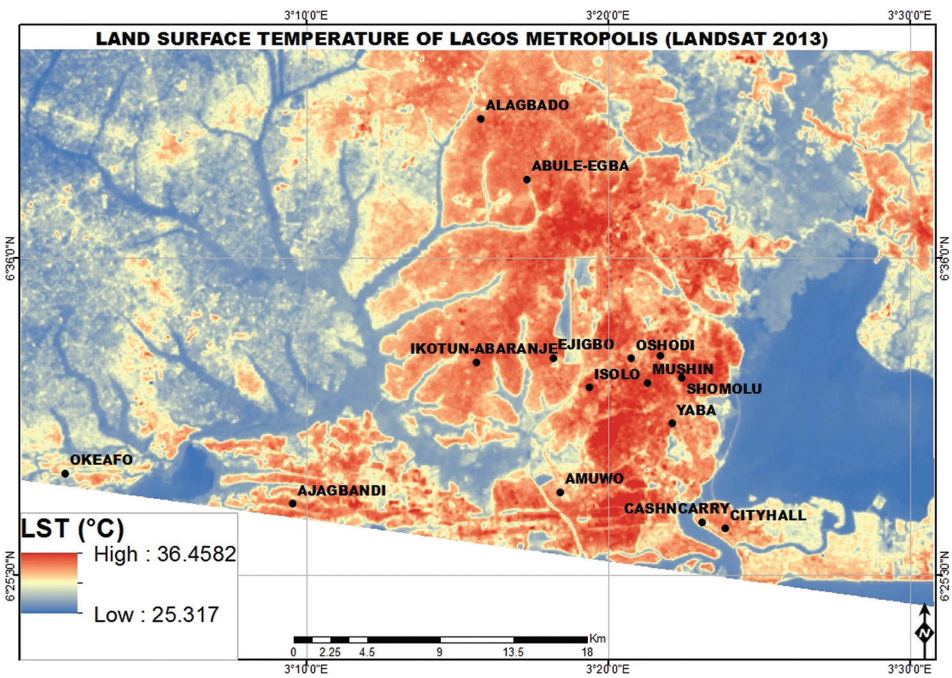

Figure 3. Land surface temperature of Lagos, 2013

and vulnerability rather than a representation of present-day conditions.

3. Results and discussion

The results of this study are primarily descriptive and reflect an exploratory spatial assessment of heat stress vulnerability using available thermal, demographic, and household-level data. The analysis provided insight into relative patterns of exposure and vulnerability across selected LGAs but does not constitute a predictive statistical model of heat risk. The descriptive approach is appropriate for the available data; however, advanced quantitative modeling would further strengthen the understanding of the drivers of vulnerability.

3.1. Exposure index

3.1.1. Heat exposure index of Lagos

Table 1 summarizes the heat vulnerability parameters obtained from the questionnaire survey. The exposure index included LST, population density, and LST hotspot classification. Sensitivity factors comprised the most vulnerable age groups (0–4 years and 65+ years), low educational attainment (no formal education, trade certificates, primary school certificates, and secondary school certificates), and income categories, including high income (₦ 100,000 and above), medium income (₦ 50,000–99,900), and low income (below ₦ 50,000). Adaptation factors included ownership of air conditioners and fans, living near water bodies, and proximity to green areas.

Figure 4 presents the population density distribution of Lagos based on projections from 2013. Five population density categories were identified. Yaba recorded the highest density, ranging from 93,320 to 339,100 persons/km². Abule-Egba, Mushin, Ilupeju, and Shomolu fell within the moderately high-density range of 45,360–93,310 persons/km². Isolo, Oshodi, and Ejigbo were classified as medium-density areas with populations ranging from 16,980 to 45,350 persons/km². Alagbado and Ikotun fell within the lower-density range of 6,417–16,970 persons/km². The observation sites with the lowest densities (88–6,416 persons/km²) were City Hall, Marina market, Amuwo-Odofin, Ajangbadi, and Oko-Afo.

Table 1. Vulnerability index parameters covered in the questionnaire

Vulnerability index parameters	Variables
Exposure	• Land surface temperature • Population density • LST hotspot analysis areas
Sensitivity	• Most vulnerable age group (0–4 and 65+) • Low education levels (no formal education, • trade certificate, primary school certificate, and West African Examinations Certificate) • Income class (high [> ₦ 100,000], medium [₦ 50,000–99,900], and low [< ₦ 50,000])
Adaptation	• Ownership of air conditioners • Ownership of fans • Living close to a water body • Proximity to grass/green space

Abbreviation: LST: Land surface temperature.

These variations in density have direct implications for heat exposure. Densely populated areas, such as Yaba, experience greater heat stress because built-up areas replace natural cover and limit passive cooling opportunities, such as airflow, tree shade, and contact with water bodies. This pattern aligns with findings from other megacities. For example, in Mumbai, rapid urban expansion led to a nearly 20% loss of green spaces over three decades and a threefold increase in high-temperature zones.[27] Similar processes are occurring in Lagos.

3.1.2. LST cluster hotspot analysis

Figure 5 shows the LST cluster hotspots across Lagos. At the 95–99% statistical confidence level, Amuwo-Odofin, Isolo, Yaba, Ilupeju, Shomolu, Alagbado, Mushin, and Ikotun were classified as significant temperature hotspots. These areas are characterized by dense built environments and limited vegetative cover, conditions that promote the absorption and retention of heat.

In contrast, Oko-Afo, Ajangbadi, City Hall, Marina market, and Abule-Egba were not classified as hotspots. These areas possess natural or built features that enhance adaptive capacity, including open spaces, tree cover, and proximity to water bodies. At the same confidence level, Oshodi and Ejigbo were categorized as cold spots, likely due to the influence of surrounding vegetation, open land, or lower built density.

These observations correspond with recent findings. In eastern India, rapid urban expansion resulted in an 8.62% reduction in vegetated areas over a 10-year period, while the relationship between LST and the normalized difference vegetation index weakened significantly.[28] Similarly, research in Thiruvananthapuram, India, documented a 118% increase in built-up areas that resulted in a measurable rise in mean LST.[29] Additional studies show that expanding tree canopy cover can reduce peak thermal stress by more than 2°C in certain urban settings, demonstrating the moderating effect of vegetation on extreme heat.[30] These findings strongly mirror the thermal conditions observed in Lagos.

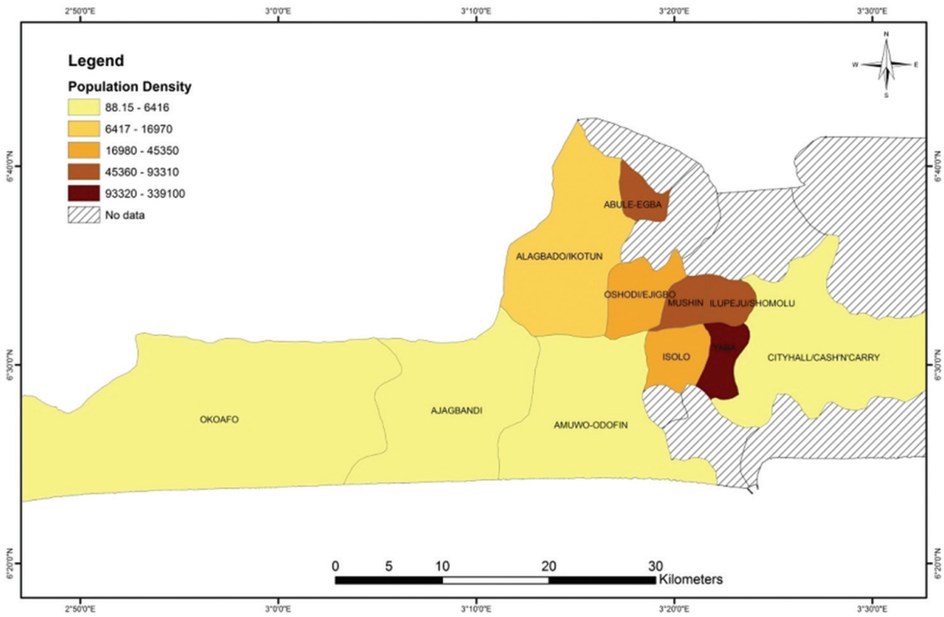

Figure 4. Population density map of Lagos

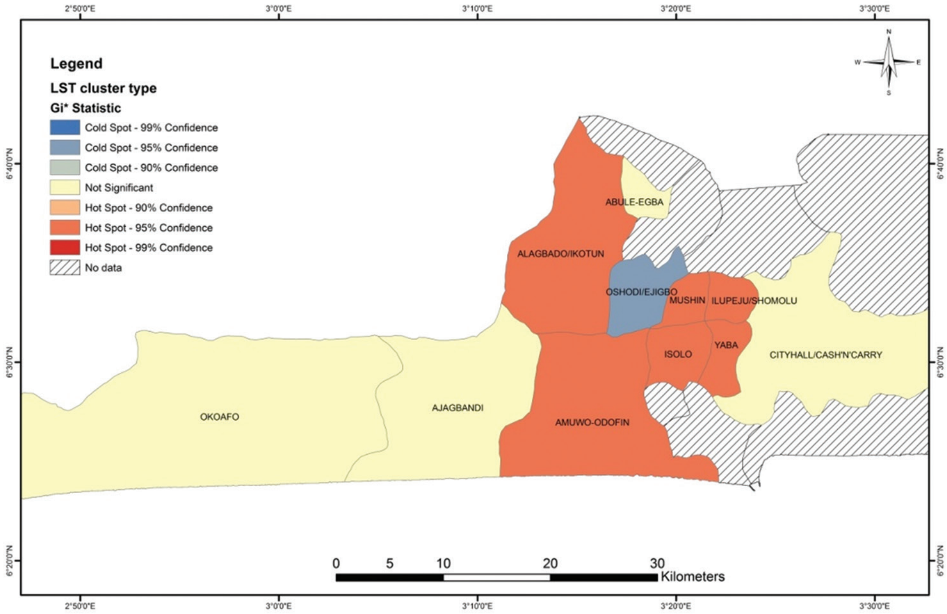

Figure 5. Land surface temperature cluster hotspot of Lagos metropolis
Abbreviation: GI: The Getis–Ord, Getis statistic at location i.

3.1.3. Heat exposure index of Lagos metropolis

Figure 6 shows the heat exposure index generated by combining population density and LST hotspot patterns. Yaba and Mushin were designated as high-exposure zones due to their high built density and limited natural cooling resources. Amuwo-Odofin, Isolo, Ilupeju, and Shomolu constituted moderate-exposure zones, reflecting a mix of built-up areas and available green spaces. Alagbado and Ikotun exhibited low exposure levels, while Oko-Afo, Ajangbadi, City Hall, Marina market, Oshodi, Ejigbo, and Abule-Egba showed minimal exposure, attributed to vegetation cover, open areas, or proximity to water bodies.

These patterns follow trends observed in other cities. For example, a fine-scale assessment in Augsburg, Germany, reported that vegetation cover and surface imperviousness have a strong influence on daytime temperatures, while building form affects nighttime conditions.[31] Lagos exhibits similar dynamics, with densely occupied neighborhoods displaying higher heat exposure and areas with vegetation and open land demonstrating greater thermal resilience.

3.2. Sensitivity index for Lagos

3.2.1. Distribution of the sensitive age group in Lagos metropolis

Figure 7 shows the spatial distribution of the most vulnerable age groups, specifically children aged 0–4 years and adults aged 65 years and above. These groups are widely recognized in heat-vulnerability studies as the most physiologically sensitive to extreme temperatures due to limited thermoregulatory capacity and higher susceptibility to heat-related illness.[32]

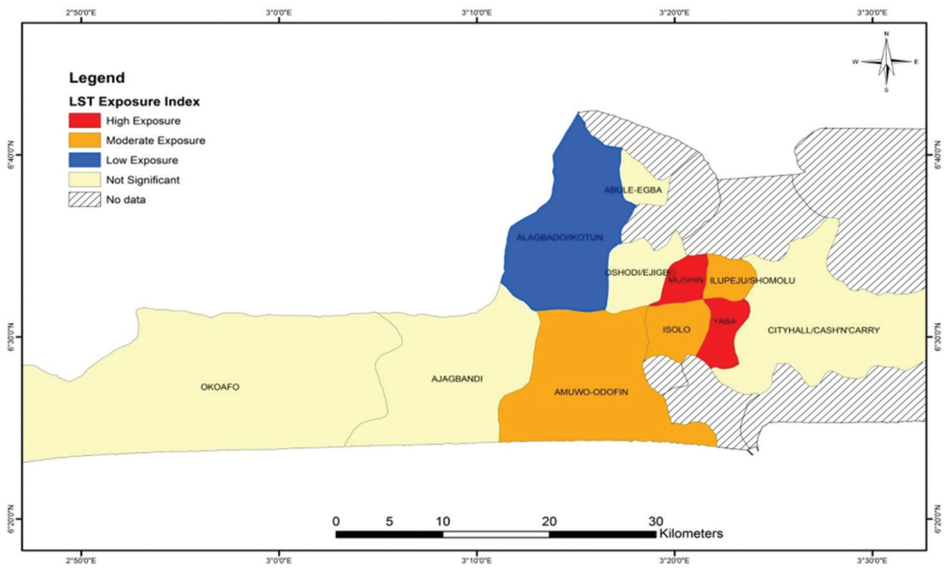

Figure 6. The land surface temperature (heat) exposure index of Lagos metropolis

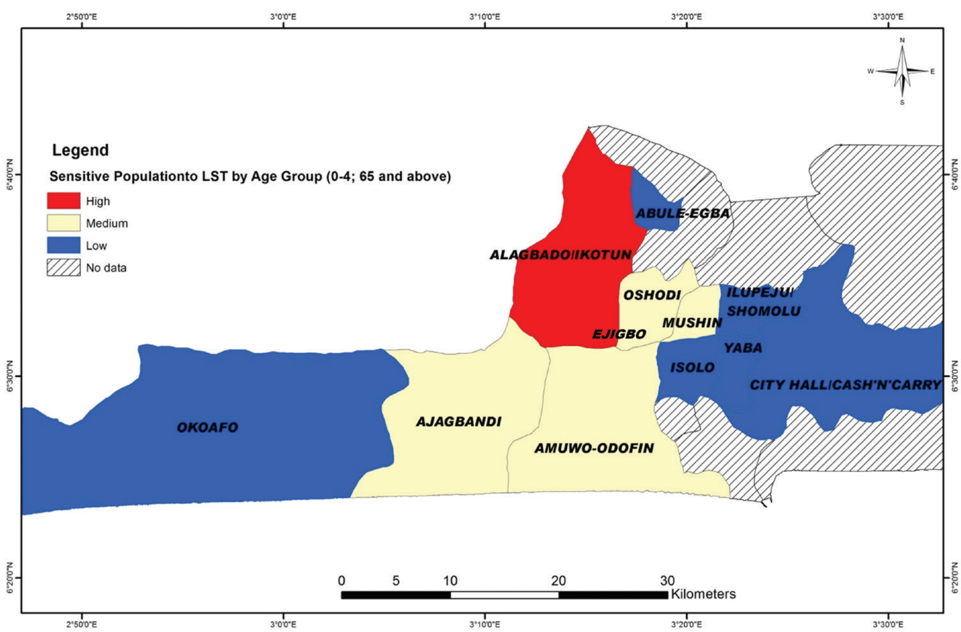

Figure 7. Distribution of the sensitive age group in Lagos metropolis

In Lagos, high populations of these age groups were found in Alagbado and Ikotun. A medium-sized population resided in Ajangbadi, Amuwo-Odofin, Oshodi, Ejigbo, and Mushin. Areas such as Oko-Afo, Isolo, Yaba, City Hall, Marina market, Shomolu, Ilupeju, and Abule-Egba had relatively low populations of the vulnerable age groups.

These patterns suggest that the western and northwestern parts of the metropolis have a higher proportion of residents susceptible to heat stress, whereas the central business district and coastal zones have lower populations of these demographic categories.

3.2.2. Educational attainment of the population in Lagos

Figure 8 illustrates the distribution of individuals with low levels of education, defined as residents without formal schooling, trade certificates, primary school certificates, or secondary school certificates. Educational attainment is a key determinant of heat vulnerability because it influences access to information, awareness of heat risks, and the ability to adopt effective adaptive behaviors.

The map indicates that the highest distribution of populations with low educational attainment was observed in Isolo, Mushin, Oshodi, and Ejigbo. High populations of low-educated individuals were also observed in Oko-Afo, Alagbado, and Ikotun. A moderate number of low-educated individuals resided in Abule-Egba. Low populations of individuals with low education levels were found in Yaba, City Hall, Marina market, and Ajangbadi, whereas Amuwo-Odofin, Ilupeju, and Shomolu have the lowest populations of individuals with low education levels.

These spatial patterns reflect the socioeconomic landscape of Lagos, where low-income, high-density neighborhoods often overlap with areas of limited educational opportunities. Such areas are likely to exhibit greater heat sensitivity due to reduced access to resources and lower adaptive capacity.

3.2.3. Population distribution of Lagos by income level

Figure 9 presents the income-based population distribution for Lagos. Income level is a major determinant of vulnerability because it affects the capacity to acquire cooling technologies, modify living environments, or relocate during extreme heat events.

High-income areas included Amuwo-Odofin, City Hall, and Marina market. These neighborhoods have access to better infrastructure, improved housing conditions, and greater purchasing power for cooling devices. Middle-income areas included Yaba, Mushin, Oshodi, and Ejigbo, whereas low-income areas included Oko-Afo, Ajangbadi, Alagbado, Ikotun, Abule-Egba, Isolo, Ilupeju, and Shomolu.

Low-income households often face the greatest challenges during extreme heat due to overcrowding, poor building materials, and limited access to cooling strategies. These socioeconomic factors strengthen the heat sensitivity component of the vulnerability assessment.

3.2.4. Combined heat sensitivity index

Figure 10 presents the combined heat sensitivity index, integrating vulnerable age groups, low educational attainment, and income levels. The results reveal that Abule-Egba, Alagbado, Ikotun, Isolo, and Oko-Afo exhibited high heat sensitivity. A medium sensitivity was observed in Ajangbadi, Oshodi, Ejigbo, Mushin, and Yaba, whereas Amuwo-Odofin, City Hall, Marina market, Ilupeju, and Shomolu exhibited low sensitivity.

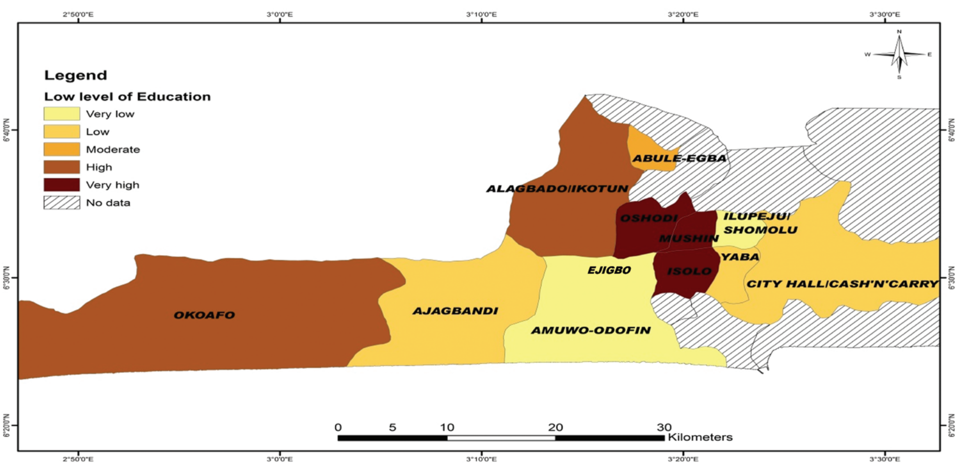

Figure 8. Distribution of population with low educational levels in Lagos metropolis

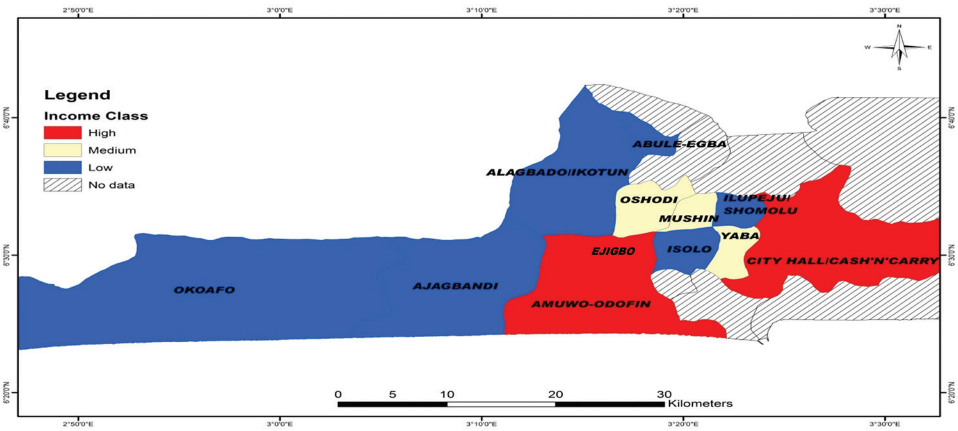

Figure 9. Population distribution in Lagos metropolis by income level

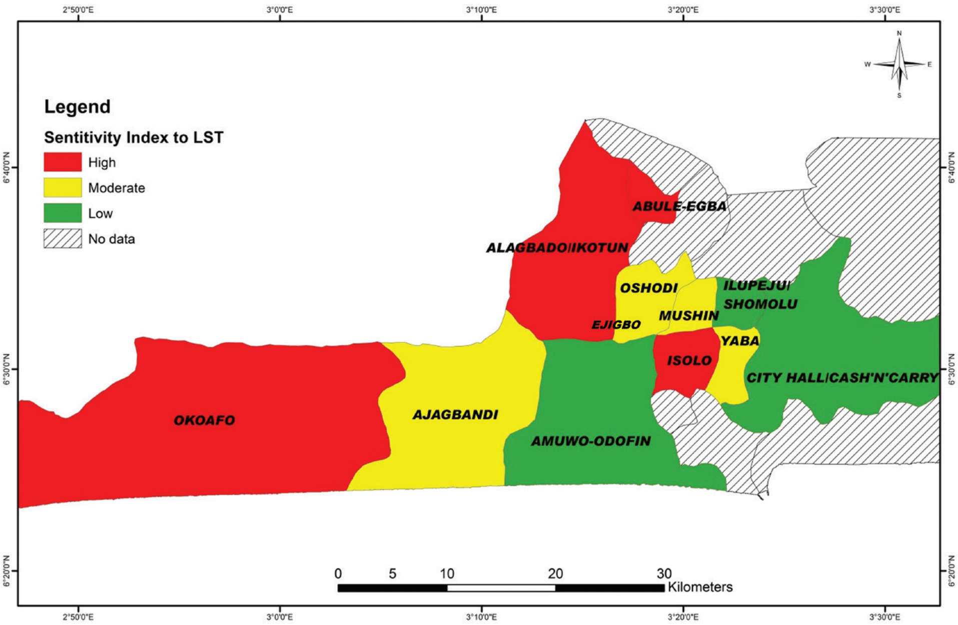

Figure 10. Overall heat sensitivity index of Lagos Metropolis

These findings align with broader research on urban heat vulnerability. For instance, a recent assessment in the Pearl River Delta region of China found that heat vulnerability is driven primarily by frequent heatwave events, demographic sensitivity, and disparities in economic and healthcare infrastructure.[21] Similar drivers are evident in Lagos, where densely populated neighborhoods with limited incomes and educational opportunities face heightened heat sensitivity.

3.3. Adaptation strategies to heat stress in Lagos

Adaptation capacity reflects the resources available to households to cope with high temperatures. In this study, adaptation strategies included ownership of air conditioners or fans, proximity to trees or green spaces, and proximity to water bodies. These strategies help reduce exposure to heat and are important indicators of communities' ability to manage thermal discomfort.

High adaptation capacity was defined as locations where the mean air conditioner ownership exceeds the overall average of 3.36 recorded across the 11 LGAs. Medium adaptation capacity refers to locations where fan ownership exceeds the overall mean of 6.63 and where residents employ at least one additional cooling strategy beyond air conditioning. Low adaptation capacity refers to LGAs that fall below the mean for both air conditioner and fan ownership

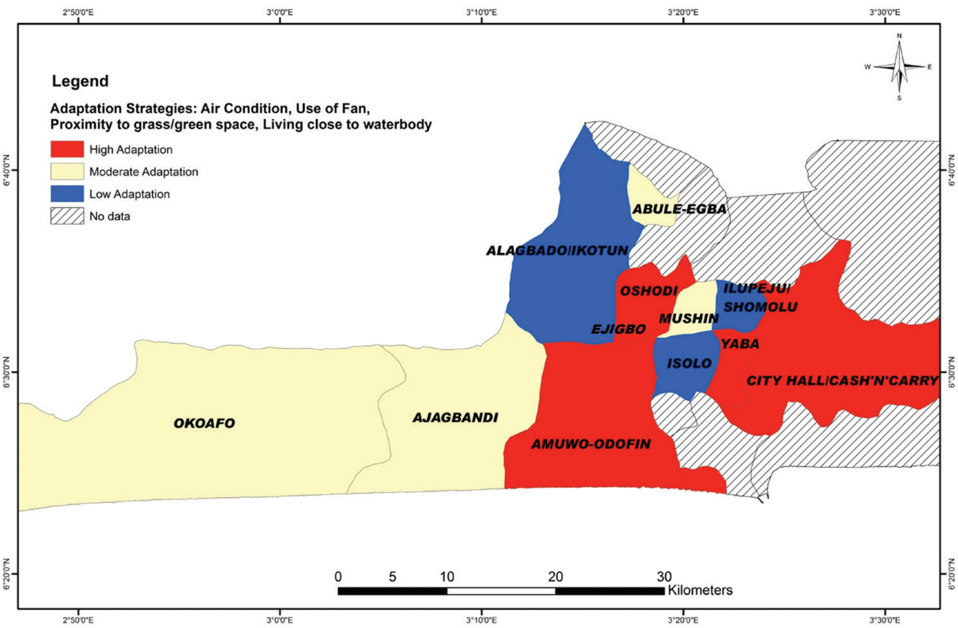

Figure 11. Distribution of adaptive strategies to heat stress in Lagos metropolis

and that rely primarily on other cooling strategies.

Figure 11 presents the spatial distribution of adaptation strategies across Lagos. The results show that Amuwo-Odofin, Oshodi, Ejigbo, Marina market, City Hall, and Yaba demonstrated high adaptation capacity. These locations benefited from relatively better housing quality, higher income levels, or improved access to infrastructure that supports mechanical cooling.

A moderate adaptation capacity was observed in Oko-Afo, Ajangbadi, Abule-Egba, and Mushin. These areas rely primarily on fans and complementary strategies, such as shading from trees or the presence of nearby water bodies. Although mechanical cooling is used, it is not as widespread as in high-adaptation zones.

A low adaptation capacity was reported in Alagbado, Ikotun, Isolo, Ilupeju, and Shomolu. These areas have limited access to mechanical cooling technologies and rely heavily on informal or natural methods to reduce heat stress. Lower adaptation levels in these neighborhoods may be linked to socioeconomic constraints, housing characteristics, or limited access to green spaces.

Overall, the spatial pattern of adaptation capacity suggests that thermal resilience in Lagos is unevenly distributed. Areas with greater economic resources and improved infrastructure exhibit greater adaptation potential, whereas low-income areas face greater challenges in coping with extreme heat conditions. These disparities highlight the need for targeted interventions that expand access to cooling resources and enhance environmental infrastructure in the most heat-sensitive communities.

3.4. Potential vulnerability to heat stress in Lagos

The combined effects of exposure, sensitivity, and adaptation determine the potential vulnerability of communities to heat stress. Figure 12 presents the integrated vulnerability classification for the 11 LGAs examined in this study. The results show distinct spatial variations, reflecting the interaction between demographic characteristics, built environment features, and access to cooling resources.

High potential vulnerability was observed in Mushin and Yaba. These neighborhoods experience combinations of high sensitivity, moderate-to-high exposure, and low adaptation capacity. In most of these areas, built density is high, informal settlements are widespread, and household access to air conditioners is limited. These conditions limit the ability of residents to cope with extreme heat. Medium vulnerability was observed in Ajangbadi, Ejigbo, Isolo, and Oshodi. A low adaptation capacity was reported in Alagbado, Ikotun, Isolo, Ilupeju, and Shomolu. These areas have limited access to mechanical cooling technologies and rely heavily on informal or natural methods to reduce heat stress. Lower adaptation levels in these neighborhoods may be linked to socioeconomic constraints, housing characteristics, or limited access to green spaces. Although not as vulnerable as the high-risk zones, these areas still require targeted interventions to improve heat resilience. From the figure, these locations fall into low-income categories.

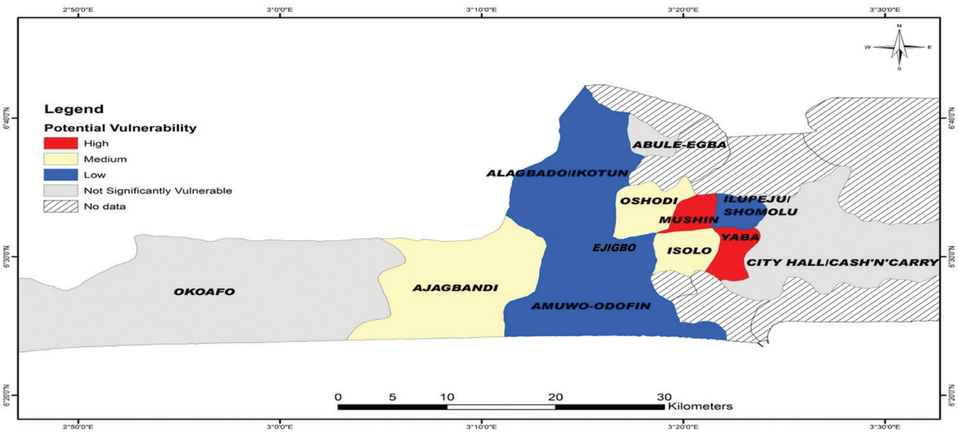

Figure 12. Potential heat vulnerability map of Lagos metropolis

The spatial distribution of potential vulnerability in Lagos reflects broader global patterns in tropical megacities, where vulnerability is often the highest in low-income areas with poor infrastructure, limited green spaces, and high population densities. Studies in cities such as Manila, Rio de Janeiro, and Dhaka similarly report that vulnerability hotspots are concentrated in rapidly urbanizing districts with limited adaptive capacity and high environmental stress.[33] The results for Lagos align with this trend, underscoring the importance of equity-focused adaptation strategies that prioritize the most vulnerable communities.

3.5. Heat vulnerability index and spatial distribution

Figure 12 shows the heat vulnerability index of Lagos and the spatial distribution of vulnerability across the metropolitan area. The results demonstrate that most of the study area falls within the medium- to high-vulnerability zones, reflecting the combined influence of dense built environments, demographic pressure, and limited adaptation capacity.

High vulnerability was observed in Abule-Egba, Ajangbadi, Alagbado, Ikotun, Ilupeju, Isolo, Oko-Afo, and Shomolu. These areas exhibit persistent high temperatures, significant proportions of sensitive populations, and limited access to cooling resources such as air conditioners or shade from vegetation. Many of these neighborhoods contain informal settlements, inadequate housing, and limited access to green spaces. These factors heighten susceptibility to heat stress and reduce households' ability to manage extreme temperatures.

Medium vulnerability was recorded in Mushin, Oshodi, and Ejigbo. These areas experience moderate exposure and sensitivity but have relatively higher adaptation capacity than the high-vulnerability zones. Residents of these areas frequently rely on mechanical cooling devices, such as fans and, in some cases, air conditioners, to reduce exposure to daytime heat. However, their vulnerability remains significant due to high population density and limited access to natural cooling features.

Low vulnerability occurred in Amuwo-Odofin, City Hall, Marina market, and Yaba. These locations benefit from lower exposure levels, reduced sensitivity, and strong adaptation capacity. Higher income levels, better building materials, and proximity to vegetated or water-based environments contribute to improved resilience. These neighborhoods demonstrate the importance of socioeconomic advantages in moderating the impacts of extreme heat.

The overall vulnerability pattern in Lagos mirrors findings from other tropical megacities. Studies in cities such as Bangkok, Jakarta, and Ho Chi Minh City show that vulnerability is shaped by a combination of demographic characteristics, LST, and access to cooling infrastructure.[34] As in Lagos, the urban poor tend to reside in the most heat-exposed and least adapted neighborhoods, reinforcing the need for policies that enhance resilience in underserved communities.

This study has several limitations. First, the use of 2013 LST and population data reflects the period for which complete and harmonized datasets were available and should be interpreted as a baseline rather than current conditions. Second, the analysis was restricted to 11 LGAs due to the absence of comparable temperature observation points and survey data in the remaining LGAs, which may limit the generalizability of the results to the wider Lagos metropolis. Third, the household survey sample of 200 respondents is small relative to the population of Lagos and was selected purposively near observation sites; therefore, the findings describe local adaptation behaviors but are not statistically representative of the entire population.

Fourth, some indicators used to operationalize exposure, sensitivity, and adaptive capacity are proxies, and the composite vulnerability index has not been validated with independent datasets. Fifth, the mapping outputs represent relative classes of vulnerability and are not probabilistic risk estimates. Future research should incorporate recent thermal datasets, larger probability-based surveys, and formal statistical or machine learning models to strengthen the predictive capacity of heat vulnerability assessments.

4. Recommendations

This study highlights the need for a more systematic approach to understanding and managing heat stress across Lagos. Future assessments should use recent, high-resolution thermal datasets, updated demographic information, and complete spatial coverage across all LGAs. Large and representative household surveys, combined with advanced analytical methods such as multivariate regression, geographically weighted regression, and machine learning, can improve scientific understanding of the relationships among LST, vegetation, population density, and social vulnerability.

From a policy perspective, Lagos requires a coordinated and proactive framework to mitigate heat-related risks. Priority actions include expanding and protecting urban green areas, incorporating heat-risk indicators into land-use planning and building regulations, promoting cool roofs and reflective building materials, and improving ventilation and shading in high-density neighborhoods. Strategies such as strengthening early warning systems, improving access to cooling options, and directing support to vulnerable groups, such as low-income households, the elderly, and those living in densely populated settlements, can help mitigate the impacts of heat.

Effective action will require collaboration among urban planners, environmental agencies, public health institutions, researchers, and community organizations. Integrating heat risk considerations into urban development, housing, public health, and climate adaptation strategies will help build a more heat-resilient and sustainable Lagos.

Continuous monitoring of LST, urban vegetation, and population health outcomes will help policymakers evaluate the effectiveness of adaptation measures and improve resilience strategies.

5. Conclusion

This study assessed the spatial pattern of heat stress vulnerability in Lagos by integrating LST, population density, demographic sensitivity, and adaptation capacity across 11 LGAs. The results show that vulnerability to heat stress varied considerably across the metropolitan area, with the highest levels concentrated in densely populated and economically disadvantaged neighborhoods. These areas experience higher temperatures, contain larger proportions of sensitive populations, and have limited access to cooling resources or green spaces.

Medium vulnerability areas benefit from improved adaptation practices, although high built density and persistent warm temperatures still present significant risks. Low vulnerability zones display strong adaptation capacity, lower sensitivity, and, in some cases, reduced exposure, largely due to better infrastructure, improved housing, and access to vegetation or water bodies.

The findings demonstrate that heat vulnerability in Lagos is shaped by the combined effects of rapid urban growth, limited green space, socioeconomic inequality, and uneven access to cooling infrastructure. As Lagos continues to expand, addressing these factors will be critical for reducing the health and environmental impacts of extreme heat. The framework from this study provides a valuable spatial insight into developing targeted adaptation strategies that support resilience in the most vulnerable communities. While the present analysis provides a useful exploratory baseline of heat vulnerability patterns across the selected LGAs, the findings highlight the need for future studies to integrate more recent thermal datasets, expand the spatial extent to include all LGAs, and apply quantitative modeling techniques, such as regression or geographically weighted regression, to further examine the relationships between vegetation cover, population density, and LST.

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Conflict of interest

The author declares no conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data for the study are available from the author on reasonable request.

Further disclosure

Part of the findings (temperature difference) was published in 2016 by MDPI in *Climate* with the title "Urban-Rural Temperature Differences in Lagos." (https://doi.org/10.3390/cli4020029)

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Appendix

LANDSAT 2013 METADATA

ORIGIN = “Image courtesy of the U.S. Geological Survey”
LANDSAT_SCENE_ID = “LC81910552013352LGN00”
TARGET_WRS_PATH = 191
TARGET_WRS_ROW = 55
DATE_ACQUIRED = 2013-12-18 December 18, 2013 (DAY-TIME)
SCENE_CENTER_TIME = 10:04:25.3497966Z (10:04 am GMT)