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| **Research Article**

Analysis of the Urban Heat Island Phenomenon and Its Impact on Land Surface Temperature in Batam City

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Abstract: Rapid urbanization in Batam City has intensified the Urban Heat Island (UHI) effect due to changes in land cover and the expansion of built-up areas. This study aims to analyze the spatial distribution of Land Surface Temperature (LST), changes in surface temperature during 2015–2025, and their relationship with land cover changes in Batam City. The research uses a quantitative descriptive approach, employing remote sensing data and Geographic Information Systems (GIS). ESG data is extracted from satellite imagery, analyzed spatially, and verified through field observations at several locations that represent urban characteristics. The results show that the distribution of ESG is influenced by the density of built-up areas, urban activities, and vegetation cover. During the period 2015-2025, there was an expansion of moderate- to high-temperature zones, especially in the northern, central, and eastern regions of Batam City, which were dominated by industrial, commercial, and residential areas. In contrast, the secondary forest and mangrove areas in the southern part have lower surface temperatures and function as natural cooling zones. These findings confirm that the conversion of vegetated land to built-up areas is the main factor driving the intensification of the UHI. Therefore, the protection of green open spaces, mangrove rehabilitation, and the implementation of green infrastructure need to be integrated into spatial planning as strategies for UHI mitigation and climate change adaptation.

Keywords: Urban Heat Island; Land Surface; Temperature; Batam City.

1. INTRODUCTION

Urbanization across Indonesian cities has drastically modified local microclimates and surface characteristics. The expansion of impervious surfaces, driven by the conversion of natural land cover to residential, industrial, and infrastructural networks, directly elevates Land Surface Temperature (LST), a critical indicator of urban thermal dynamics (Anurogo et al., 2022). Empirical remote sensing studies consistently confirm that empirical shifts toward built-up environments significantly accelerate localized surface warming (Mohiuddin & Mund, 2024). This phenomenon is of great importance because rising surface temperatures not only alter the physical characteristics of cities but also affect environmental sustainability, energy efficiency, and urban resilience to climate change (Patel et al., 2024).

As a primary economic driver in the Riau Islands Province, Batam City exemplifies this rapid urban transformation. The proliferation of industrial estates, transport infrastructure, and commercial hubs has systematically encroached upon municipal green spaces, undermining the environment's natural capacity to regulate thermal balance. Such uncontrolled urban growth poses a severe challenge to sustainable development, as it sharply intensifies warming trends at local to regional scales (Shen & Zhao, 2024). In addition, Batam's character as an archipelago city with very rapid development of industrial estates results in different land use configurations compared to metropolitan cities in Indonesia, so that the surface heat distribution pattern is estimated to have unique spatial characteristics (Anurogo et al., 2022 Gustin & Roziqin, 2019).

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This disparity, in which urban core temperatures exceed those of surrounding rural or natural areas, defines the Urban Heat Island (UHI) effect. Fundamentally, UHI stems from the thermal properties of artificial materials like concrete and asphalt, which absorb and retain solar radiation far more efficiently than vegetated landscapes (Mohajerani et al., 2017). This structural heat retention is further exacerbated by anthropogenic waste heat from transportation, industrial manufacturing, and intensive air conditioning use. Concurrently, the loss of canopy cover reduces latent heat flux via evapotranspiration, thereby locking sensible heat within the urban fabric (Hasanudin et al., 2025). Furthermore, background climatic baselines and variability in surface composition dictate how severely these thermal shifts manifest across different urban topologies (Naserikia et al., 2022).

As an expanding island city, Batam exhibits highly heterogeneous LST patterns driven by localized building densities, structural layouts, and uneven green space distribution. Industrial corridors and packed residential wards act as distinct thermal hotspots. Previous assessments on Batam Island confirm that structural density directly correlates with heightened UHI intensity (Anurogo et al., 2023), a pattern mirrored across diverse global urban typologies where built-up transitions reliably increase thermal thresholds (Zwolska et al., 2024).

The ramifications of UHI extend beyond surface temperature metrics; they profoundly disrupt public health, socio-economic stability, and environmental quality. Persistent thermal stress degrades outdoor comfort, increases the incidence of heat-related illnesses, and traps localized air pollutants. Moreover, rising ambient temperatures trigger a feedback loop of increased energy consumption via mechanical cooling, escalating carbon emissions and worsening local climate vulnerability (Setiawati et al., 2021). Consequently, understanding these coupled thermal-urban dynamics is vital for managing public health risks and energy infrastructure demands in highly populated centers (Rees et al., 2024). However, most previous research has still focused on mapping the distribution of ESG or identifying UHI descriptively. Studies that comprehensively integrate the spatial variation of ESG in Batam City are still relatively limited (Gustin et al., 2023).

Based on the research gap, this study aims to analyze the spatial distribution of Land Surface Temperature (LST) and identify the relationship between changes in land cover characteristics and the intensity of Urban Heat Island in Batam City using a remote sensing approach based on satellite imagery. The novelty of this research lies in integrating spatial analysis of ESG with the characteristics of urban development in rapidly growing archipelago cities, yielding a more comprehensive understanding of urban thermal patterns that serves as the basis for preparing Urban Heat Island mitigation strategies and sustainable urban planning. The results of this study are expected to make a scientific contribution to the development of urban climate studies in tropical regions as well as an input for policymakers in designing spatial planning that is more adaptive to climate change.

2. RESEARCH METHODS

This study uses a quantitative descriptive approach, utilizing remote sensing technology and a Geographic Information System (GIS) to analyze the spatial distribution of Land Surface Temperature (LST) in Batam City (Figure 1). This approach was chosen because it provides accurate spatial information on surface temperature characteristics and changes in thermal conditions due to urban development. Remote sensing is used as the primary source of thermal infrared data from satellite imagery, while GIS is used for data preprocessing, ESG parameter extraction, spatial analysis, visualization, and the preparation of surface temperature distribution maps.

The analysis was conducted using data from two observation periods, namely 2015 and 2025, to identify changes in surface temperature distribution patterns resulting from land-use development and urbanization. Furthermore, the results of image interpretation were verified through field observation (ground check) at several locations representative of industrial estates, settlements, green open spaces, and coastal areas. This verification process aims to ensure that the image interpretation results conform to actual field conditions, particularly building density, vegetation conditions, and surface material types that affect surface temperature variations.

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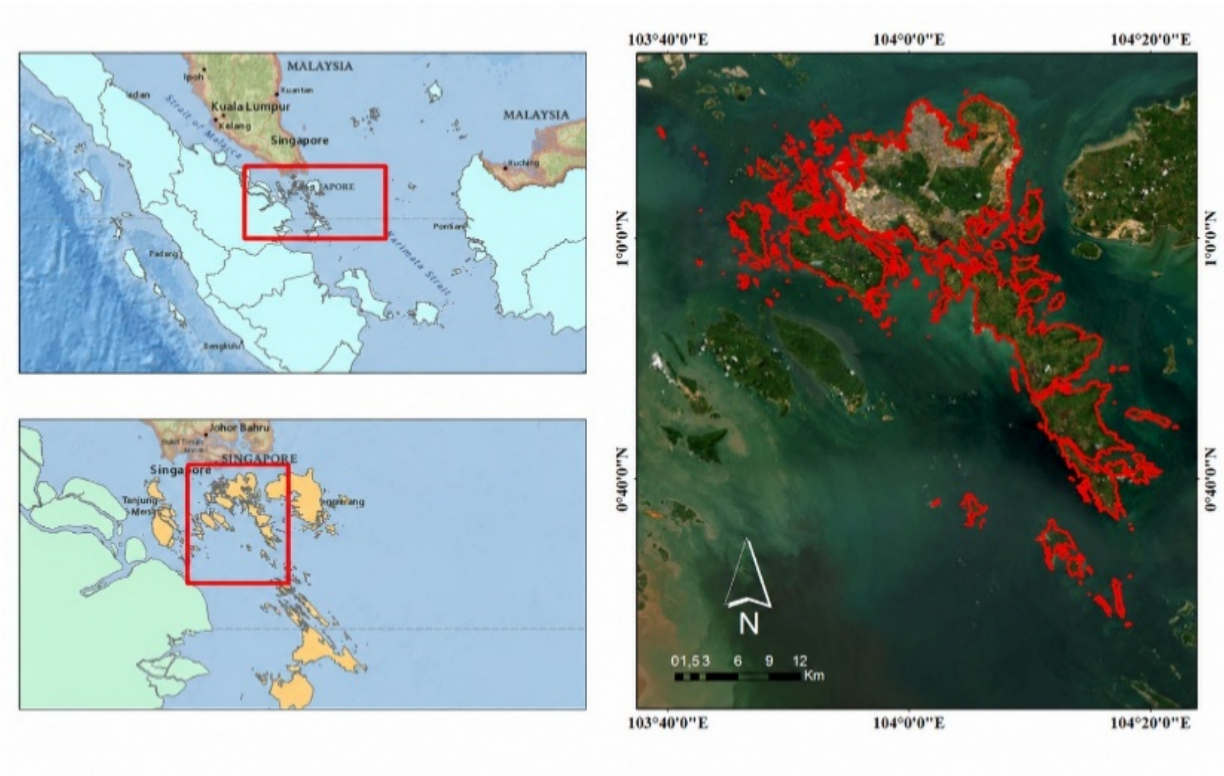

Figure 1. Location Map of the Study Area in Batam City, Indonesia.

The primary dataset comprises Landsat 8 imagery, selected for its high-resolution thermal infrared bands. The workflow for extracting LST from raw digital numbers involves five systematic calculation phases:

Top of Atmosphere (TOA) Spectral Radiance Conversion

Raw Digital Numbers (DN) representing uncalibrated sensor data are first converted to Top-of-Atmosphere (TOA) spectral radiance. This initial calibration step standardizes the data, allowing the digital values to be converted into absolute temperature scales (Kelvin and subsequently Celsius) necessary for climate analysis (Gandri, 2022).

$$L_\lambda = M_L \times Q_{cal} + A_L$$

Brightness Temperature (BT) Derivation

Following radiance calibration, the values from the Thermal Infrared Sensor (TIRS) Band 10 are converted into at-satellite Brightness Temperature (BT). This calculation assumes a blackbody surface and utilizes sensor-specific thermal calibration constants to yield temperature values in Celsius (Du et al., 2015).

$$BT = \frac{K2}{\text{In}\left(\frac{K1}{L\lambda} + 1\right) - 273.15}$$

Vegetation Index (NDVI) Mapping

To quantify surface greenness and structural density, the Normalized Difference Vegetation Index (NDVI) is computed. NDVI leverages the differential reflectance of vegetation between the Near-Infrared (NIR) and visible Red bands, providing a normalized ratio critical for scaling surface emissivity (Mohiuddin & Mund, 2024). NDVI is used to assess vegetation cover.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

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Land Surface Emissivity (LSE) Estimation

Land Surface Emissivity accounts for the non-blackbody behavior of real-world surfaces. This study estimates emissivity by calculating the Fractional Vegetation Cover derived directly from normalized NDVI thresholds (Sobrino et al., 2004). First, the Proportion of Vegetation (PV) is calculated using:

$$PV\left(\frac{NDVI - NDVI\ min}{NDVI\ max - NDVI\ min}\right)2$$

Then, emissivity is calculated as:

$$E = 0.0004 \times PV + 0.986$$

Land Surface Temperature (LST) Calculation

Finally, the actual LST is computed by correcting the brightness temperature with the derived surface emissivity values. The resulting pixels reflect true land surface conditions in degrees Celsius (Gandri, 2022). The resulting land surface temperature values are classified into several categories to facilitate interpretation (Table 1).

$$LST = \frac{BT}{1 + \left(\frac{\lambda \times BT}{\rho}\right) In\varepsilon}$$

Table 1. Land Surface Temperature Classification

No	Class	Temperature
1	Low	<28°C
2	Moderate	28°C – 32°C
3	High	> 32°C

3. RESULTS AND DISCUSSION

Distribution of Land Surface Temperature (LST) in Batam City

The empirical processing of the 2015 and 2025 LST datasets reveals distinct spatial variations across Batam City, categorized into four thermal tiers: very low, low, moderate, and high (Figure 2). The geographic distribution of these zones demonstrates a direct structural link between human surface modifications, building densities, and localized microclimates. Thermal hotspots (classified as "High" and rendered in red) are heavily clustered in northern and central Batam. These zones function as the city's urban core, housing manufacturing complexes, logistics ports, commercial centers, and dense residential grids.

The intense thermal footprint here highlights the efficient heat-retaining capacity of artificial urban surfaces. Asphalt roads, metal roofing, and concrete walls trap solar radiation during the day and continuously release sensible heat back into the boundary layer, keeping surface temperatures elevated. Conversely, cool zones ("Low" to "Very Low", rendered in green) are predominantly situated in southern Batam and its peripheral archipelagos. These environments remain dominated by secondary forests, coastal mangroves, and contiguous green canopies. The depressed LST profiles in these sectors underscore the power of natural land cover: active vegetation regulates surface energy budgets by converting solar radiation into latent heat through evapotranspiration, thereby preventing surface overheating and maintaining ambient humidity. This is in line with findings from (Estoque et al., 2017), which show that vegetation, water, and impermeable surface aggregation patterns strongly determine temperature variations, so that seas, reservoirs, mangroves, and green spaces are likely to create sharp cooling pockets between heat corridors.

These results show that the distribution of ESG in Batam City is not random but follows a pattern of land use development. Areas with high building density tend to have higher surface temperatures than areas that are still dominated by vegetation. This difference is due to the physical characteristics of the surface, where urban materials such as concrete, asphalt, and metal have different reflectance values (albedo) and heat storage capacities compared to vegetation cover. Proutsos et al., (2025) also stated that the presence of vegetation significantly influences the distribution of ESG because vegetated surfaces generally exhibit surface temperatures close to ambient air temperature, thereby reducing heat accumulation.

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On the other hand, built-up areas tend to increase sensible heat flux and decrease latent heat flux due to limited evapotranspiration. This condition causes more heat energy to be stored and released back into the atmosphere, raising the surface temperature. On the other hand, areas still dominated by vegetation can maintain the surface energy balance through evapotranspiration and shading, resulting in more stable thermal conditions.

A comparison between the 2015 and 2025 baselines shows significant spatial expansion of the urban thermal footprint. Over the 10-year period, moderate- and high-temperature zones have expanded outward, reclaiming areas previously classified as cool. The 2025 map shows an expanding dominance of red and yellow pixels across northern, central, and eastern Batam. This structural shift is a direct result of rapid, unmitigated urban development; extensive tracts of vegetated land have been cleared to make way for industrial developments and housing projects. This widespread removal of natural canopies has compromised Batam's regional thermal buffer, causing substantial localized warming.

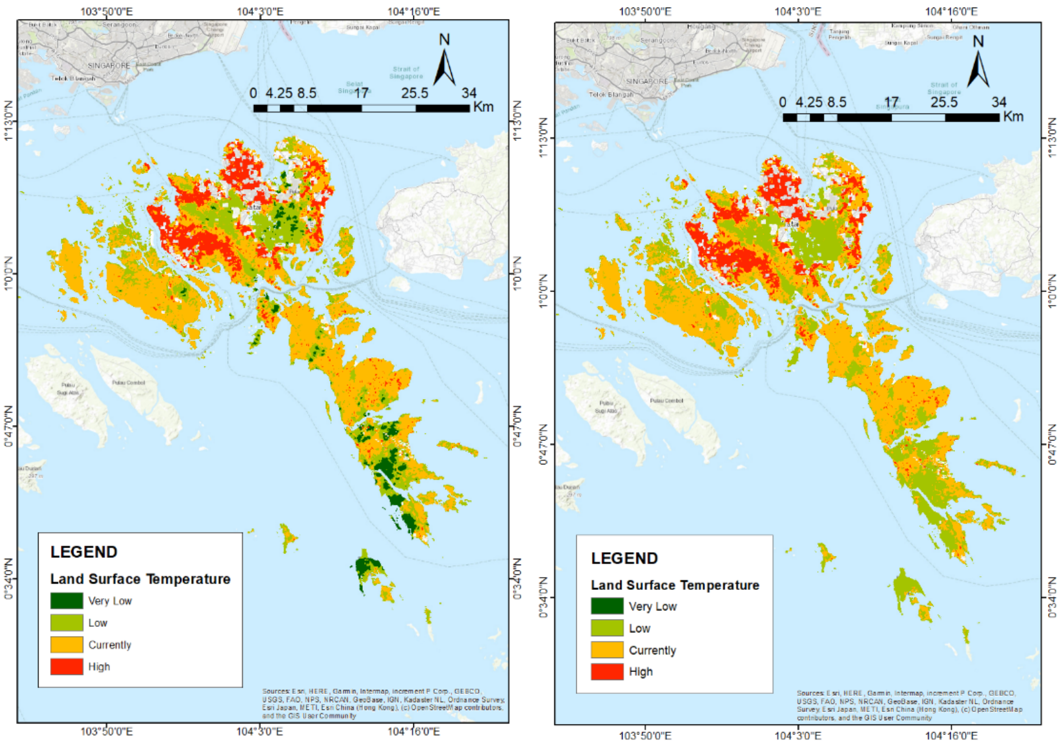

Figure 2. Land Surface Temperature Map of Batam City (a) 2015 & (b) 2025

Impacts of the Urban Heat Island Phenomenon on Surface Temperature Conditions in Batam City

The intensification of Batam's UHI is fundamentally structural, driven by the replacement of natural carbon sinks with impervious surfaces. As green open spaces are replaced by industrial infrastructure, the landscape loses its natural capacity to disperse heat. This structural shift is compounded by anthropogenic waste heat emissions from motor vehicles, industrial processing plants, and HVAC systems. High building densities further worsen this effect by lowering urban aerodynamic roughness, trapping heat within narrow street canyons and slowing cooling winds. The consequences of this expanding thermal footprint are multi-faceted. At the environmental level, elevated LST correlates with increased energy demand, creating a feedback loop in which households and businesses rely heavily on air conditioning, driving up municipal electricity demand. This intensive energy use spikes ambient heat emissions and localized carbon footprints. Furthermore, thermal accumulation alters urban wind profiles and traps particulate matter, degrading local air quality. From a socio-ecological perspective, the UHI directly threatens public health. Prolonged exposure to elevated urban temperatures causes heat stress, dehydration, and exhaustion, while compounding underlying cardiovascular and respiratory issues. This risk is unevenly distributed, falling most heavily on vulnerable populations, such as the elderly and young children, living in high-density, low-vegetation urban neighborhoods.

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In addition to increasing surface temperatures, the Urban Heat Island (UHI) phenomenon can reduce the quality of life for urban communities by increasing energy consumption, decreasing thermal comfort, and increasing the risk of health problems from exposure to high temperatures. These findings are in line with research in Fuzhou City, which showed that the urbanization process contributes to an increase in the intensity of UHI, thereby leading to an increase in urban temperature and lowering the thermal comfort level of the community. This condition is relevant to Batam City, which is developing as an international industrial area with a very high level of urbanization, industrial activity, and population mobility. These characteristics have the potential to accelerate the increase in surface temperature if not balanced with the provision of green open space and adaptive spatial management strategies. Therefore, Urban Heat Island mitigation needs to be an integral part of sustainable urban development policies by strengthening green infrastructure, increasing vegetation cover, and implementing land-use planning to reduce heat accumulation in urban areas.

The Influence of Urban Heat Island with Land Cover Change

The spatial distribution of Land Surface Temperature (LST) shows a close relationship between land-cover change and the intensity of the Urban Heat Island (UHI) in Batam City. Areas that experience changes in land use or cover play a significant role in increasing soil surface temperature, such as the conversion of vegetation areas to industrial areas, settlements, and transportation networks (Faqe Ibrahim, 2017). These conditions indicate that urbanization has altered the biophysical characteristics of the surface, thereby increasing the absorption of solar radiation and reducing the natural cooling capacity. As a result, built-up areas develop as heat accumulation centers, while areas that still retain vegetation cover show relatively lower surface temperatures.

Physically, urban materials such as concrete, asphalt, and metal have a higher heat capacity and thermal conductivity than vegetation and are able to absorb large amounts of solar energy during the day and release it slowly so as to maintain a high surface temperature (Tan et al., 2024; Ziaeemehr et al., 2023). In contrast, vegetation acts as a temperature controller through evapotranspiration, shading effect, and increased air humidity. This condition causes built-up areas to have a higher sensible heat flux and lower latent heat flux than vegetated areas. Research (Massaro et al., 2023) also shows that vegetated surfaces tend to have temperatures close to ambient air temperature, so vegetation functions as an effective thermal buffer, reducing the increase in ESG.

The findings of this study are consistent with the results of Roba & Tabor (2025), which show that the expansion of built-up areas is the dominant factor driving increases in surface temperatures in various developing cities due to reduced vegetation cover. Similar results are also confirmed by (Mahata et al., 2024), who found that an increase in the proportion of impervious surfaces is positively correlated with an increase in the intensity of Urban Heat Islands. Batam City shows a pattern evident in the spread of medium- to high-temperature zones across the northern, central, and eastern regions, which are centers of industrial, trade, and residential activities. On the other hand, the southern region, which is still dominated by secondary forests and mangroves, exhibits a relatively lower surface temperature, serving as a natural cooling zone.

The results of this study show that land-cover change is the primary driver of the spatial dynamics of surface temperature in Batam City. Batam's characteristics as an archipelago city make green open spaces and mangrove ecosystems play a strategic role in mitigating the intensity of the Urban Heat Island. Therefore, controlling land conversion, protecting green areas, rehabilitating mangroves, and implementing green infrastructure need to be integrated into urban spatial planning. The strategy not only has the potential to lower surface temperature and reduce the intensity of UHI, but also supports the development of cities that are more adaptive to climate change and improves the environmental quality and thermal comfort of the community.

4. CONCLUSION

This study shows that the spatial distribution of Land Surface Temperature (ESG) in Batam City is greatly influenced by changes in land cover, density of built-up areas, and urban activities. During the period 2015–2025, the medium- to high-temperature zones experienced significant expansion, particularly in the northern, central, and eastern regions, which are dominated by industrial areas, settlements, and transportation networks. In contrast, areas that still retain vegetation cover, such as secondary forests and mangroves, exhibit lower surface temperatures, serving as natural cooling zones. The results of this study

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confirm that the conversion of vegetated land to built-up areas is the primary driver of increased surface temperature and the intensity of the Urban Heat Island (UHI) in Batam City.

The findings of this study contribute to understanding the spatial dynamics of ESG and the relationship between land cover change and UHI intensity in rapidly growing archipelago cities. The study's findings indicate that land-conversion control, protection of green open spaces and mangrove ecosystems, and implementation of green infrastructure need to be integrated into spatial planning as strategies for UHI mitigation and climate change adaptation. Further research is suggested that integrates biophysical indicators, such as NDVI, NDBI, and NDWI, with meteorological variables to produce a more comprehensive analysis of urban thermal dynamics.

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