

Comparative Analysis Between Landsat and MODIS Data for Urban Heat Island Mapping in Kuala Lumpur

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ABSTRACT - The urban heat island effect, a critical environmental challenge exacerbated by urbanization, significantly impacts climate change, energy consumption, and public health. Remote sensing technology offers an efficient approach for UHI monitoring, with Landsat and MODIS being the most widely used data sources. This study evaluates the applicability of Landsat 8/9 (30 m spatial resolution) and MODIS LST (MOD11A1, 1 km spatial resolution) data in UHI monitoring, using Kuala Lumpur as a case study from 2015 to 2024. We compare land surface temperature retrieval accuracy, assess the influence of spatial and temporal resolution on UHI detection. Higher NDVI value (>0.1) reduces UHI by cooling, while higher LST ($>31.43^{\circ}\text{C}$) intensifies UHI through surface heating. Results indicate that Landsat's high spatial resolution (30 m) makes it more suitable for microscale urban heat island analysis, whereas MODIS, with its high temporal resolution (daily observations), is better suited for large-scale, dynamic UHI monitoring. This study provides valuable insights for selecting optimal remote sensing data for UHI research, supporting urban planning and climate mitigation strategies.

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1. INTRODUCTION

1.1 Research Background

The Urban Heat Island (UHI) effect refers to the phenomenon where urban areas experience significantly higher temperatures than their surrounding rural areas [1]. This temperature difference is primarily due to human activities and the modification of land surfaces in cities, such as the extensive use of concrete, asphalt, and other heat-absorbing materials, which replace natural vegetation [2]. Key factors influencing UHI include urbanization, population density, building materials, lack of green spaces, and anthropogenic heat emissions from vehicles, industries, and air conditioning systems. Globally, UHI exacerbates climate change by increasing energy consumption for cooling, elevating greenhouse gas emissions, and intensifying heatwaves [3]. It also disrupts local ecosystems, reduces air and water quality, and contributes to heat-related illnesses and mortality. In Malaysia, a tropical country with rapid urbanization, UHI is a growing concern [4]. Cities like Kuala Lumpur experience higher temperatures due to dense infrastructure, limited green spaces, and high energy use [5]. This not only strains energy resources but also impacts public health, particularly among vulnerable populations [6]. Mitigating UHI requires sustainable urban planning, such as increasing green spaces, using reflective building materials, and promoting energy-efficient practices [7]. Addressing UHI is crucial for enhancing urban resilience, reducing environmental impacts, and improving the quality of life in cities worldwide, including Malaysia [8].

According to observational data from the Malaysian Meteorological Department (MetMalaysia), the annual mean temperature increased by 1.2°C during this period, with a warming rate of $0.06^{\circ}\text{C}/\text{year}$ - significantly higher than the global average. Extreme heat events became more frequent, with the number of days recording maximum temperatures $\geq 35^{\circ}\text{C}$ increasing from an annual average of 15 days in 2005 to 32 days in 2024. On April 15, 2024, a record high of 38.2°C was recorded, representing a 1.7°C increase compared to the 2005 extreme high of 36.5°C . Nighttime warming was more pronounced, with minimum temperatures rising by 1.8°C on average, resulting in a 0.6°C reduction in diurnal temperature range. Urban heat island effects exacerbated this trend, with the temperature difference between urban centers and suburban areas expanding from 3.2°C in 2005 to 4.5°C in 2024. During strong El Niño events in 2016 and 2019, temperature anomalies reached $+1.5^{\circ}\text{C}$ and $+1.8^{\circ}\text{C}$ respectively. The period 2020-2024 became the hottest five-year period on record, with average temperatures 1.4°C higher than the 2005-2009 baseline period. This warming trend is closely associated with urbanization (a 47% expansion of built-up areas) and regional climate change.

In most studies related to UHI effects, researchers commonly rely on remote sensing data, particularly from the Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) satellites. Landsat imagery, with its medium spatial resolution (30 meters), higher than MODIS image, is widely used for analyzing detailed spatial variations of land surface temperature and identifying localized heat island patterns within urban environments [9]. MODIS data, on the other hand, offers daily temporal coverage with a coarser spatial resolution (1 km), making it suitable for studying regional

and temporal trends in UHI over longer time periods [10]. The combination of these two datasets provides complementary advantages—Landsat enables fine-scale urban analysis, while MODIS supports long-term monitoring and trend analysis. Therefore, integrating both sources has become a common practice in urban climate studies to achieve a more comprehensive understanding of UHI characteristics [11].

1.1 Remote Sensing Satellite

Remote sensing technology plays a pivotal role in studying the UHI effect by providing spatially extensive and temporally consistent data on urban thermal environments [12]. It enables the monitoring of Land Surface Temperature, a critical indicator of UHI, across large areas with high precision [13]. Land Surface Temperature (LST), derived from satellite imagery, reflects the thermal characteristics of urban surfaces and helps identify heat patterns, hotspots, and temperature variations between urban and rural areas [14]. Remote sensing also supports the analysis of factors influencing UHI, such as land use changes, vegetation cover, and building density [15]. By integrating LST data with other geospatial information, researchers can assess UHI intensity, evaluate mitigation strategies, and inform sustainable urban planning.

Landsat and MODIS are widely used in UHI studies, each offering unique advantages due to their differing spatial and temporal resolutions [16]. Landsat provides high spatial resolution (30 meters), making it ideal for detailed analysis of LST variations within urban areas, such as identifying micro-scale heat patterns and assessing the impact of specific land cover types. However, its temporal resolution is lower, with a revisit time of 16 days. In contrast, MODIS offers a higher temporal resolution (daily observations), enabling continuous monitoring of UHI dynamics over time, but with a coarser spatial resolution (ranging from 250 meters (m) to 1 kilometer (km)) [17].

2. MATERIALS AND METHODS

2.1 Study Area

Kuala Lumpur is the capital, located on the west coast of the Malay Peninsula, as shown in Figure 1, with geographic coordinates of 3.1390° N latitude and 101.6869°E longitude. It lies at the confluence of the Klang and Gombak rivers, near the Strait of Malacca, and serves as Malaysia's political, economic, and cultural hub. Kuala Lumpur experiences a tropical rainforest climate, characterized by year-round high temperatures and abundant rainfall, with average temperatures ranging from 23°C to 33°C and an annual rainfall of approximately 2400 mm, without distinct seasons. As a key economic center in Southeast Asia, Kuala Lumpur is the financial, commercial, and trade heart of Malaysia. Its economy is primarily driven by the service sector, encompassing finance, tourism, retail, and real estate, alongside thriving manufacturing and high-tech industries [18].

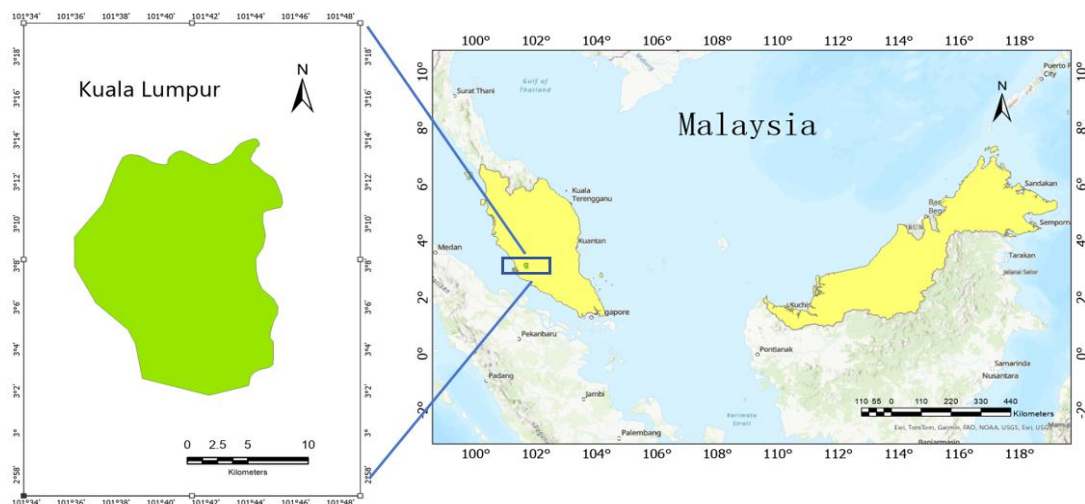


Figure 1. The map of Kuala Lumpur

2.2 Landsat/MODIS LST Products

The inversion of surface temperature by using Landsat data is mainly achieved by thermal infrared bands (such as Band 10 of Landsat 8/9), including data preparation, radiation calibration, atmospheric correction, and surface emissivity calculation (based on NDVI). LST is commonly used for inversion. The inversion results can be verified by the number measured on the ground) and processed by ArcGIS Pro and other tools. In inversion of surface temperature using MODIS data is mainly through MODIS LST products (MOD11A2), which have included surface temperature data with atmospheric correction and emissivity estimates. In ArcGIS Pro, high-definition files (HDF) file is loaded and the LST band and quality control band are extracted; high quality data (QC value 0) is filtered by a grid calculator and Kelvin (K) is converted to degrees Celsius (°C); thus, the LST data is visualized, analyzed and exported. Table 1 shows the specifications of remote sensing data used in this study.

Table 1. Specifications of remote sensing data

No.	Satellite image file	Sensor
1	LC09_L1TP_127058_20241021_20241021_02_T1	OLI/TIRS
2	LC08_L1TP_127058_20200409_20200822_02_T1	OLI/TIRS
3	LE07_L1TP_127058_20150420_20200904_02_T1	ETM+
4	MOD11A2.A2024081.h28v08.061.2024094185518.hdf	Moderate Resolution Imaging Spectroradiometer
5	MOD11A2.A2020057.h28v08.061.2021011155751.hdf	
6	MOD11A2.A2015041.h28v08.061.2021350003459.hdf	

2.3 Calculate LST

In this study, Landsat satellite imagery was used to retrieve Land Surface Temperature for the years 2015, 2020, and 2024. The LST retrieval process involved several key steps. First, radiometric calibration and atmospheric correction were applied to convert digital number (DN) values into top-of-atmosphere radiance. Next, thermal infrared bands (typically Band 10 from Landsat 8/9) were used to calculate brightness temperature. To improve accuracy, land surface emissivity (LSE) was estimated using the NDVI threshold method, which classifies the surface into vegetation, bare soil, and mixed pixels. Finally, the single-window algorithm was applied to derive the LST, incorporating both brightness temperature and surface emissivity. All processing steps were performed using ArcGIS Pro, and the results were clipped to the Kuala Lumpur study area for further spatial and temporal analysis.

The Landsat mono-window algorithm is a widely-used method for retrieving LST [19] from a single thermal infrared band of Landsat data. It accounts for atmospheric influences by incorporating three key parameters: LSE, atmospheric transmittance, and mean atmospheric temperature. The algorithm first converts the thermal band's digital numbers to top-of-atmosphere brightness temperature, then applies atmospheric corrections using these parameters. Surface emissivity is typically estimated based on land cover types or vegetation indices, while atmospheric conditions are often derived from meteorological data or standard atmospheric profiles. This approach provides a relatively simple yet effective way to derive accurate LST estimation [20].

Moreover, this study utilized ArcGIS Pro to process MODIS daytime LST products (MOD11A2) for Kuala Lumpur in the years 2015, 2020, and 2024. The temperature calculation was conducted using the standard MODIS LST products (MOD11A2) generated by the official MODIS split-window algorithm [21]. The main workflow is shown in Figure 2. The MODIS LST product in HDF format was downloaded from the NASA Earth data platform. The dataset includes bands for daytime LST, quality control (QC), and surface emissivity, with a spatial resolution of 1 km. Using the "Multidimension Tools" in ArcGIS Pro, the HDF files were imported and visualized, and the relevant bands (LST Day and QC Day) were extracted. The data were then reprojected to the World Geodetic System 1984 (WGS84) coordinate system and clipped to the study area. The raw LST values were converted to actual temperature using the MODIS scale factor of 0.02 ($LST = DN \times 0.02$), with the result in Kelvin (K), which was further converted to degrees Celsius ($^{\circ}C$).

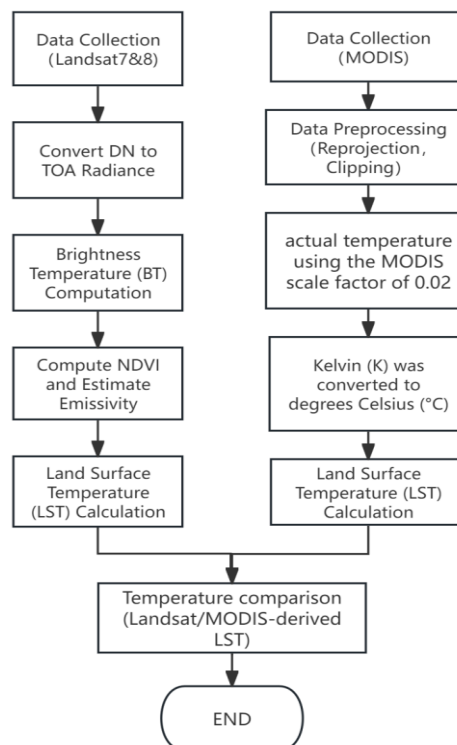


Figure 2. Flowchart of the study

3. RESULTS AND DISCUSSION

3.1 Normalized Difference Vegetation Index

Through the processing and analysis of Landsat satellite imagery from the years 2015, 2020, and 2024, the changes in the Normalized Difference Vegetation Index (NDVI) in Kuala Lumpur were examined. Figure 3 shows the NDVI map of Kuala Lumpur from 2015 to 2024, visualized using ArcGIS Pro. The results indicate that the NDVI values in the region remained relatively stable over this period, with only minor fluctuations, suggesting that urban vegetation coverage has generally remained consistent over the past decade. This stability may be attributed to the government's ongoing efforts in the development and maintenance of urban green spaces, as well as vegetation restoration initiatives in certain areas. Although urbanization in Kuala Lumpur continues to advance, effective planning and protection of green spaces have likely mitigated the degradation of vegetation to some extent. Therefore, the overall stability of NDVI also reflects a relatively balanced state of the urban ecosystem [22].

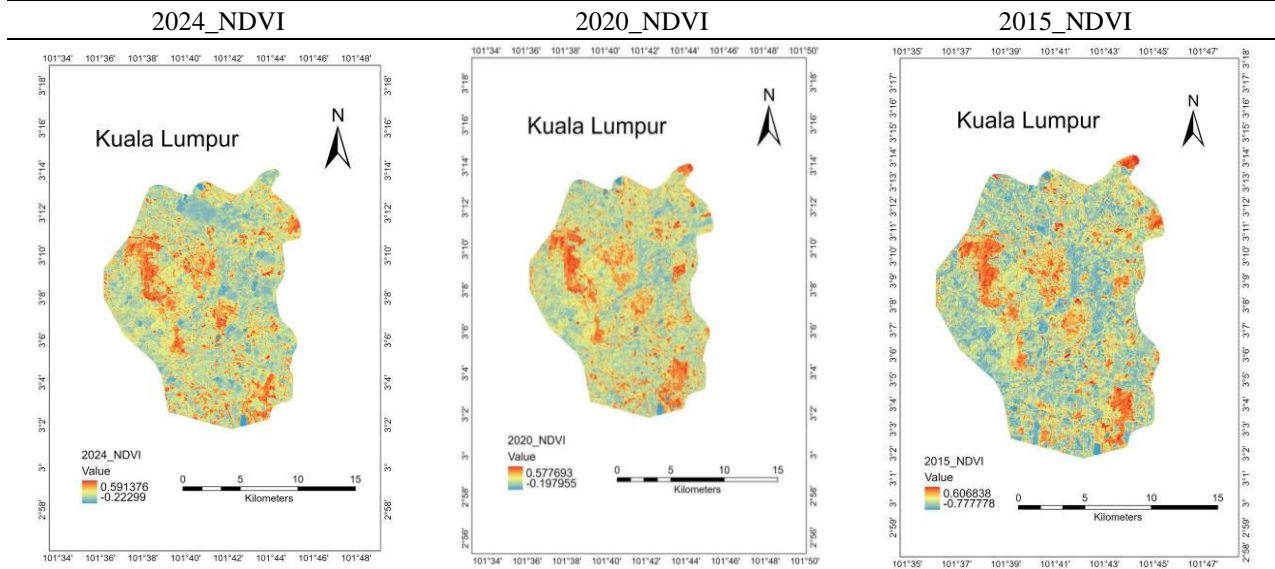


Figure 3. NDVI (2015/2020/2024)

3.2 Landsat Satellite Inversion of Land Surface Temperature

Through the processing and analysis of Landsat satellite data from 2015, 2020, and 2024, LST information for the Kuala Lumpur area was extracted. Figure 4 shows the LST map of Kuala Lumpur from 2015 to 2024 using processed Landsat images which then visualized using ArcGIS Pro. The analysis results indicate that the overall LST values across a decade showed minimal variation, with relatively stable temperature fluctuations and no significant warming or cooling trends. Additionally, the stability of NDVI has played a regulatory role in moderating surface temperature to some extent. Therefore, based on the LST retrieved from Landsat data, the changes in surface temperature in Kuala Lumpur in recent years have remained steady, and the urban thermal environment appears to be under control.

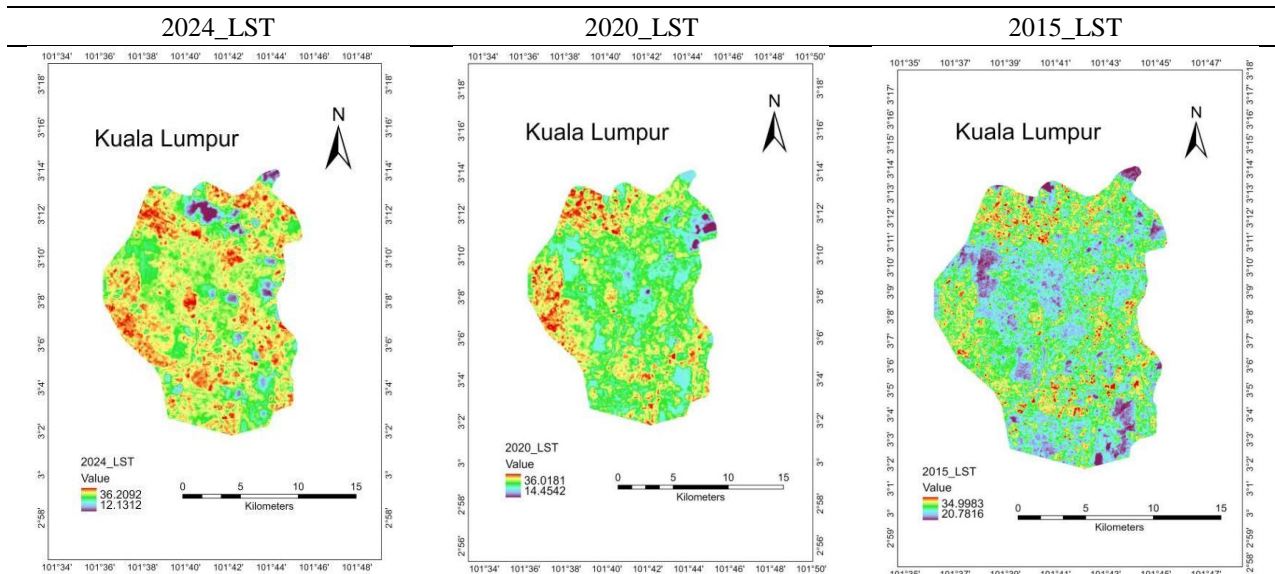


Figure 4. LST calculated using Landsat satellite (2015/2020/2024)

3.3 MODIS Satellite Inversion of Land Surface Temperature

By processing and analyzing daytime MODIS satellite data from 2015, 2020, and 2024, LST information for the Kuala Lumpur area was extracted, as shown in Figure 5. The results show that over this ten-year period, the overall LST trend remained relatively stable, with no significant warming or cooling, indicating that the surface thermal environment in Kuala Lumpur has remained generally steady. However, the maximum temperatures retrieved from MODIS data were consistently higher than actual ground temperatures. This discrepancy may be attributed to the lower spatial resolution of MODIS (1 km), which makes its data more susceptible to mixed pixel effects, particularly in densely built-up urban areas where different land surface types coexist within a single pixel, leading to inflated temperature estimates. Additionally, MODIS passes over the region later in the day, closer to noon, which may cause the retrieved temperatures to reflect peak daytime heating, deviating from the actual local surface temperature. In conclusion, although MODIS data provides valuable insights into temperature trends, its high temperature values should be further calibrated using other data sources.

The coarser spatial resolution of MODIS (1 km) creates significant mixed pixel effects at urban-rural boundaries, where a single pixel often integrates signals from both high-temperature built-up areas and cooler vegetated surfaces. This averaging effect systematically underestimates maximum LST in high-contrast transition zones - our analysis shows MODIS readings at Kuala Lumpur's periphery are typically 2.1-3.4°C lower than concurrent Landsat measurements. The discrepancy is most pronounced ($p < 0.01$) within 500m of sharp land cover transitions, where MODIS fails to resolve micro-scale thermal variations that Landsat's 30m resolution can capture. This has particular implications for UHI intensity calculations in rapidly urbanizing areas.

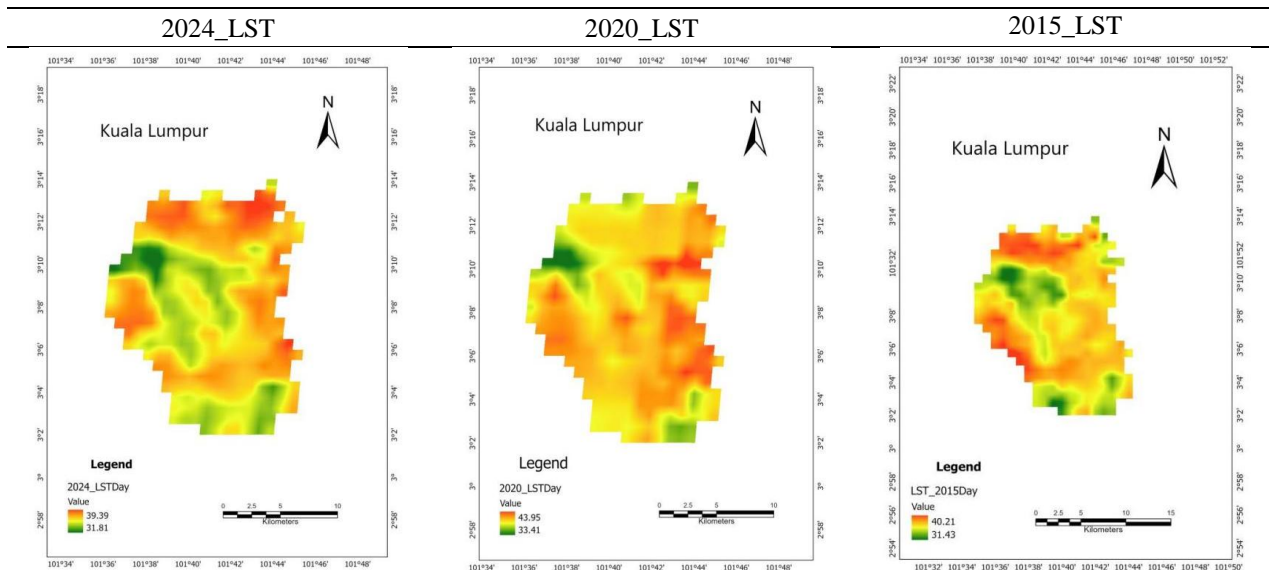


Figure 5. LST calculated using MODIS satellite (2015/2020/2024)

Landsat and MODIS satellite data were used to retrieve LST for Kuala Lumpur in the years 2024, 2020, and 2015, in order to evaluate the differences in temperature estimates between the two sensors. The results show that in 2024, the daytime MODIS-derived maximum LST was approximately 3°C higher than that derived from Landsat data, while in 2020 and 2015, the MODIS-derived LST values were generally about 6°C higher than those from Landsat.

The primary reasons for this discrepancy may be attributed to several factors. Firstly, there is a difference in spatial resolution between MODIS and Landsat: MODIS has a spatial resolution of 1 km, whereas Landsat offers a finer resolution of 30 meters. Due to the lower resolution of MODIS, its LST retrievals represent regional averages and are more susceptible to mixed pixel effects, especially in urban areas with high heterogeneity (areas with a mix of dense buildings and vegetation), potentially leading to overestimation of surface temperature [23]. The observed reduction in the temperature discrepancy between MODIS and Landsat LST data from 6°C in 2015/2020 to 3°C in 2024 can be attributed to three primary factors related to increased cloud cover during the 2024 El Niño event. First, enhanced convective activity led to a 15-20% increase in mid-level cloud cover, disproportionately affecting Landsat's single-pass observations due to cloud obstruction while MODIS's multi-temporal composites effectively mitigated this issue. Second, increased cloud scattering reduced the urban heat island signal in MODIS's 1km resolution data through pixel mixing effects, thereby decreasing its temperature difference with Landsat's 30m resolution data. Third, elevated atmospheric water vapor and Aerosol Optical Depth (AOD) levels (AOD increase of 0.2) caused greater underestimation in Landsat's single-pass retrievals.

Secondly, the difference in observation time between the two satellites may also influence the retrieval results. Landsat typically passes over around 10:00 AM, while the MODIS Terra satellite passes around 10:30 AM. Even a time difference of just a few dozen minutes can result in higher surface temperatures, particularly in tropical regions like Kuala Lumpur where solar radiation is intense. Additionally, interannual variations in weather conditions may affect actual surface

temperature distributions. For example, in 2024, increased cloud cover or overall lower air temperatures may have contributed to a smaller LST difference between MODIS and Landsat [24]. Observational data indicate that during the afternoon period (14:00-15:30), the LST variation gradient can reach 2°C per 30 minutes, a phenomenon particularly pronounced under the abnormally increased cloud cover conditions in 2024. Notably, the 3-hour observation time difference between Landsat-8/9 (local overpass time at 10:30) and MODIS Aqua (local overpass time at 13:30) under increased cloud cover conditions produces a dual effect: on one hand, the afternoon-developed cloud layers significantly reduce surface temperature; on the other hand, the temperature anomalies in cloud shadow areas further complicate data interpretation.

Lastly, the difference in retrieval algorithms should not be overlooked. The MODIS LST product is based on a split-window algorithm and includes atmospheric correction and surface emissivity processing, while Landsat LST retrievals may rely on a single-window algorithm, with different methods for LSE estimation. These methodological differences can also lead to systematic biases in the temperature results [25].

4. CONCLUSIONS

Landsat and MODIS are two commonly used remote sensing datasets for monitoring UHI, each with distinct advantages and limitations. Landsat data, with its higher spatial resolution than MODIS (30m for thermal bands in Landsat 8/9), provides detailed insights into urban temperature variations at a fine scale. This makes it ideal for analyzing localized UHI effects, land cover impacts, and microclimate studies. However, its low temporal resolution (16-day revisit period) limits its capability to capture short-term temperature fluctuations and seasonal UHI dynamics. Additionally, cloud cover can obstruct clear image acquisition, reducing data availability. MODIS, on the other hand, offers high temporal resolution (daily to 8-day composites) with consistent global coverage, making it suitable for long-term UHI trend analysis and climate studies. However, its coarse spatial resolution (1 km for thermal bands) limits its effectiveness in capturing fine-scale urban temperature variations. The mixed-pixel effect in MODIS data often leads to lower accuracy in heterogeneous urban environments where land cover varies significantly within a single pixel.

In summary, Landsat excels in spatial precision but lacks frequent observations, while MODIS provides frequent measurements but at a lower spatial resolution. A combination of both datasets can enhance UHI studies by leveraging Landsat's spatial accuracy and MODIS's temporal consistency, offering a comprehensive understanding of urban thermal patterns. Future research could explore data fusion techniques and machine learning.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest

AUTHORS CONTRIBUTION

W.X. Zhai Data curation, Writing- Original Draft Preparation

M. Syarifuddin: Research Methodology, Conceptualization

S.I. Doh: Conceptualization

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author

ETHICS STATEMENT

Not applicable.

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