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JURNAL ILMU LINGKUNGAN
Volume xx Issue x (xxxx) : xx-xxxx *ISSN 1829-8907*

The Impact of Urbanization Scale on Ecological Conditions and Surface Heat Patterns: A Comparative Study of Jakarta – Semarang City

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ABSTRAK

Urban Heat Island (UHI) merupakan tantangan lingkungan yang kritis di kota-kota padat penduduk, namun studi komparatif di berbagai skala urbanisasi masih terbatas. Studi ini meneliti bagaimana skala urbanisasi—yang tercermin dari kepadatan bangunan dan tutupan vegetasi—memengaruhi kondisi ekologis di Jakarta (kota besar) dan Kota Semarang (kota metropolitan). Suhu Permukaan Tanah (LST), *Urban Thermal Field Variance Index* (UTFVI), *Normalized Difference Vegetation Index* (NDVI), dan *Normalized Difference Building Index* (NDBI) diperoleh dari citra Landsat 9. Tutupan lahan diklasifikasikan menggunakan algoritma Random Forest, dan fluks energi permukaan diperkirakan melalui Algoritma Keseimbangan Energi Permukaan untuk Lahan (SEBAL). Analisis regresi menghubungkan NDVI dan NDBI dengan UTFVI, dan uji Mann–Whitney U menilai perbedaan antara kedua kota tersebut. Hasil menunjukkan bahwa Jakarta memiliki NDBI yang lebih tinggi dan NDVI yang lebih rendah daripada Kota Semarang ($p < 0,007$). Suhu permukaan tanah rata-rata Jakarta mencapai 28,7°C dengan hanya 17,95% wilayahnya yang berada dalam kondisi termal "sangat baik", dibandingkan dengan 26,2°C dan 74,68% di Kota Semarang. NDBI berkorelasi lebih kuat dengan UTFVI ($R^2 \approx 0,56$) daripada NDVI ($R^2 \approx 0,32$). Dalam regresi berganda, NDBI memiliki efek pemanasan yang lebih kuat di Jakarta, sedangkan NDVI memiliki efek pendinginan yang lebih besar di Kota Semarang. Keseimbangan energi permukaan Jakarta didominasi oleh fluks panas sensibel ($141 W/m^2$), sedangkan Kota Semarang didominasi oleh fluks panas laten ($143 W/m^2$). Strategi mitigasi kontekstual direkomendasikan: desain perkotaan vertikal dan reflektif untuk Jakarta, dan konservasi vegetasi dengan infrastruktur hijau-biru untuk Kota Semarang.

Kata kunci: Tutupan Lahan, Suhu Permukaan Tanah, Neraca Energi Permukaan, Urbanisasi, UTFVI.

ABSTRACT

Urban Heat Island (UHI) presents a major sustainability issue in large urban areas with a lot of people, yet comparative studies across different urbanization scales remain limited. This study examines how urbanization scale which reflects by building density and vegetation cover, influences ecological conditions in Jakarta (a megacity) and Semarang City (a metropolitan city). Land Surface Temperature (LST), Urban Thermal Field Variance Index (UTFVI), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI) were derived from Landsat 9 imagery. The Unexpected Forest algorithm was employed to categorise coverage of land, and the Surface Energy Balance Algorithm for Land (SEBAL). Regression analysis related NDVI and NDBI with UTFVI, and Mann–Whitney U tests assessed differences between the two cities. Results show that Jakarta has a higher NDBI and NDVI than Semarang City ($p < 0,007$). Jakarta's mean LST reached 28,7 °C with only 17,95% of its area in "very good" thermal condition, compared to 26,2 °C and 74,68% in Semarang City. NDBI correlated more strongly with UTFVI ($R^2 \approx 0,56$) than NDVI ($R^2 \approx 0,32$). In multiple regression, NDBI had a stronger warming effect in Jakarta, whereas NDVI had a greater cooling effect in Semarang City. Jakarta's surface energy balance was ruled by sensible heat flow ($141 W/m^2$), whereas Semarang City's was controlled by latent heat flow ($143 W/m^2$). Contextual mitigation strategies are recommended: vertical and reflective urban design for Jakarta, and conservation of vegetation with green–blue infrastructure for Semarang City.

Keywords: Land Cover, Land Surface Temperature (LST), Surface Energy Balance, Urbanization, UTFVI.

Citation: Lugina, SM., and June, T. (2026). The Impact of Urbanization Scale on Ecological Conditions and Surface Heat Patterns: A Comparative Study of Jakarta – Semarang City. Jurnal Ilmu Lingkungan, xx(x), xx-xx, doi:10.14710/jil.xx.x.xxx-xx

1. INTRODUCTION

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UHI is commonly characterised by a situation where temperatures in city's center are greater than its surounding areas. When it comes to population growth and populated cities, UHI can become a critical issue due to its impact on many aspects of life, especially human health and ecological conditions. For example, the World Health Organization (WHO, 2025) has reported a correlation between heat risk and cardiovascular, respiratory disorders, mental health problems, and increased risks of accidents and infectious disease transmission. The rising temperatures also worsen mortality, morbidity, and reduce cognitive performance (Meadows et al., 2024; Mazloumi et al., 2014). These risks underscore the urgent need to address UHI impacts in densely populated areas.

High-population-density areas, especially metropolitan or megapolitan cities like Jakarta and Semarang City, experience more frequent heat stress in daily life. Rapid urbanisation tends to add more impervious facilities like buildings, roads, and settlements. This can change the albedo and the arrangement of energy on the ground (Soeparyanto et al., 2022). These factors will lead to more heat being absorbed in the area, thus raising the temperature, thereby increasing the potential for damage to the natural world (Soeparyanto et al., 2022; Januari et al., 2024). One of the famous approaches to address these challenges is the oversight of green areas in the downtown.

Previous studies have mentioned that urban open greenery is very important due to its ability to absorb carbon dioxide (CO^2) and enhance oxygen (O^2) levels in the air. Moreover, it's also important for reducing air temperature, improving thermal comfort, and providing cultural ecosystem service to urban communities (Saninah et al., 2023). Moreover, factors specific to each city, including density of population, land use, and the effects of UHI can greatly influence the effectiveness of urban green open spaces, indicating that mitigation approaches for the UHI effect might differ in each city. (Yang et al., 2022). Hence, mitigation strategies should be addressed to a specific city's condition.

Jakarta has experienced significant environmental degradation and rising temperatures since 1986 (Syamsudin and Lestari, 2017). The population of Jakarta was reported to exceed 10 million in the 2020 census, with a density of 14.555 people/km2 (BPS DKI Jakarta, 2021). In contrast, Semarang City, the capital of Central Java Province, had about 1.6 million residents and a density of 4.425 people/km^2 (BPS Kota Semarang, 2021). This comparative analysis addresses a research gap in understanding thermal environmental dynamics, especially in how different urban surface characteristics at varying scales of urbanization can influence ecological conditions.

Jakarta and Semarang City are selected based on urbanization level, population density, administrative status, and contrasting land-cover configuration. As a megacity, Jakarta tends to picture higher socio-ecological complexity and anthropogenic levels, while Semarang City, as the provincial capital and a still-growing metropolitan area, presents a clearer spatial configuration with substantially vegetated areas and a relatively centralized urban center. This comparison provides a more comprehensive understanding of how urbanization scale affects surface energy fluxes and ecological sustainability, while strengthening the conceptual basis for contextual strategies to reduce the effects of urbanisation at various stages. The goal of this inquiry is to comparatively describe the influence of building density and urban vegetation, at different scales of urbanization, on ecological conditions, examine surface heat distribution patterns and ecological energy balance components descriptively, and formulate strategic recommendations based on the level of urbanization of the studied area for better thermal mitigation measures.

2. MATERIALS AND METHODS

This investigation utilises an approach known as comparative studies that incorporates conventional telemetry data and statistical methods to quantify the differences in urban heat impacts between two distinct urbanization scales.

2.1. Location of Study Areas

This study was observed on Jakarta and Semarang City areas (Figure 1). Geographically, Jakarta is situated on the northwest coast of Java Island, precisely between 6°10′–6°22′ S and 106°44′–106°58′ E, whereas Semarang City is situated on the island's northern central coast between 6°50′–7°10′ S and 110°15′–110°35′ E. The differences in urbanization scale, land cover configuration, and anthropogenic pressure make them suitable for comparative analysis of UHI's impacts.

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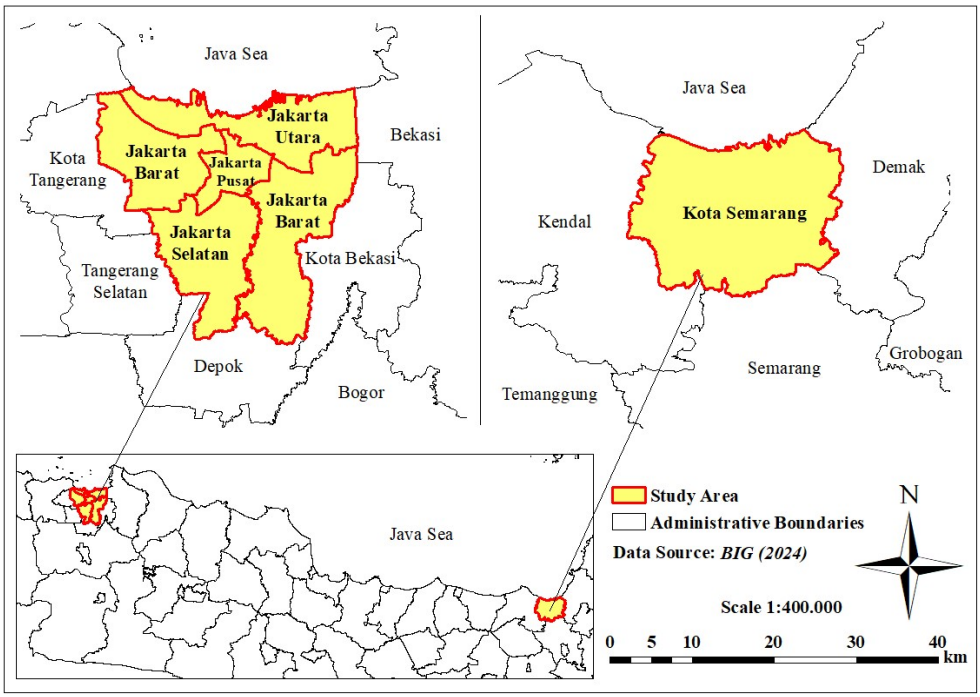


Figure 1. Study area locations of Jakarta (megacity) and Semarang City (metropolitan city), Indonesia. Administrative boundaries were obtained from BIG (2024).

2.2. Data

The Primary dataset comprised of Landsat 9 Collection 2 Level 2 images taken in 2024 acquired from the USGS. Two avail scenes for each study area were averaged because identical acquisition dates for Jakarta and Semarang City were unavailable. This approach should be able to minimize temporal variation and assure comparability between cities, consistent with a previous study, which recommended using multiple scenes within one period to avoid reliance on a single potentially biased acquisition (Knudby et al., 2014).

To validate Landsat-derived LST, Moderate Resolution Imaging Spectroradiometer (MODIS) MOD11A2.061 products were used as reference. Administrative boundaries were gained from the Indonesian Geospatial Information Agency (BIG) for delineating study areas. All datasets used are outline in Table 1.

Table 1. Summary of datasets used in this study

Data	Spatial Resolution	Period	Utility	Sources
Citra Landsat 9 OLI-2/TIRS-2	30 m	Jakarta: 30 July 2024 15 August 2024 (path 122/ row 64) Semarang City: 16 July 2024 17 August 2024 (path 120/ row 65)	• Ecological condition analysis (UTFVI, NDBI, NDVI) • Land cover classification • Energy balance component analysis	USGS
LST Citra MODIS MOD11A2.061	1 km	Jakarta: 27 July 2024 12 August 2024 Semarang City: 19 July 2024 12 August 2024	• Validation of estimated surface temperature data	USGS
Regional Administrative Boundaries		-	• Study area boundaries	BIG

Both Landsat and MODIS scenes were averaged due to different acquisition dates.

2.3 Data Processing and Analysis

The research procedure began with the acquisition of surface temperature data from Landsat 9 OLI-2/TIRS-2 and MODIS LST imagery, which were processed using cloud masking. The data were later clipped to fit the administrative limits of both cities involved in the study. A research workflow chart is summary in Figure 2.

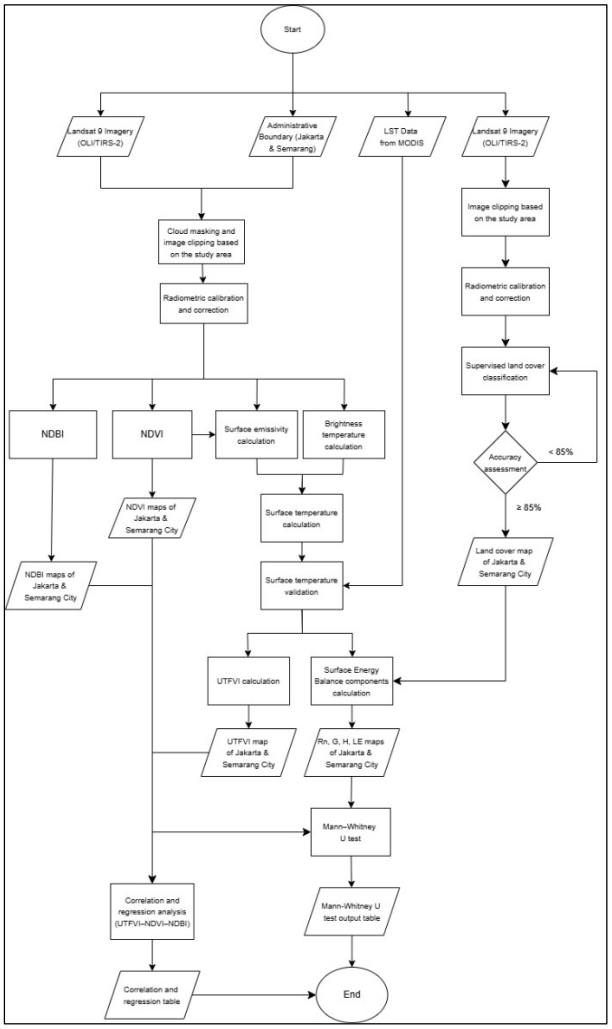


Figure 2. Research flowchart

2.3.1. Image Processing and Classification

The technique known as the Random Forest was used to oversee the grouping based on land cover, with a proportion of training and test samples of 80:20 referring to the research of Adhitya et al. (2023). The classification consists of four classes: water bodies, vegetation, open land, and built-up land. These four classes were selected to simplify the classification structure and reflect the dominant landscape elements typical of the urban area studied. The amount of sample points was calculated based on Eq. 1 (Hasyim et al. 2017).

$$n = \frac{N}{(N.e^2)+1} \quad (1)$$

where n refers to the number of samples, N denotes study area size, and e is an error margin (5%). Samples for training and testing purposes were carefully selected by utilizing the imagery available on Google Earth, representing land cover classes such as vegetation, built-up areas, water, and bare soil

The correctness in coverage of land grouping was verified through the use of a confusion matrix or error matrix that was subsequently employed to compute user's, producer's, overall, and kappa accuracy. The confusion matrix can be viewed in Table 2. The formulas for computing the above measures are provided in Eqs. 2–5 (Novianti 2021):

Table 2. Confusion matrix

Land Cover Class Result	Actual Class				
	A	B	C	D	Total
A	X_{ii}				X_{i+}
B		X_{ii}			
C			X_{ii}		
D				X_{ii}	
Total	X_{+i}				N

User's accuracy:

$$(X_{ii}/X_{+i}) \times 100\% \quad (2)$$

Producer's accuracy:

$$(X_{ii}/X_{i+}) \times 100\% \quad (3)$$

Overall accuracy:

$$((\sum_{i=1}^{r} x_{ii})/N) \times 100\% \quad (4)$$

Kappa accuracy:

$$[(N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} x_{i+}x_{+i})/N^2-\sum_{i=1}^{r} x_{i+}x_{+i})] \times 100\% \quad (5)$$

where N denotes the total number of pixels in the image; Xi+ represents the sum total of pixels in row i; X+i refers to the sum total of pixels in column i; Xii represents the diagonal element of the contingency matrix for row i and column i

NDVI (Eq. 6) and NDBI (Eq. 7) were calculated to quantify vegetation cover and built-up intensity, respectively, with their classifications shown in Table 3 and Table 4.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (6)$$

$$NDBI = \frac{SWIR1 - NIR}{SWIR1 + NIR} \quad (7)$$

where NIR, RED, and SWIR1 denote the near-infrared, red, and shortwave infrared band reflectances.

Table 3. NDVI Classification. Higher values of NDVI indicate denser vegetation cover and better ecological health.

NDVI Value	Classification
NDVI < 0	Non-Vegetation
0 ≤ NDVI < 0,154	Very Low Greenness
0,154 ≤ NDVI < 0,241	Low Greenness
0,241 ≤ NDVI < 0,431	Moderate Greenness
NDVI ≥ 0,431	High Greenness

Source: modified from (Isnaeni and Prasetyo, 2021).

Table 4. NDBI Classification. Increased NDBI values reflect higher built-up density, typically correlating with higher urban surface temperatures.

NDBI Value	Classification
NDBI < 0	Non-Built-up
0 ≤ NDBI < 0,050	Low Density
0,050 ≤ NDBI < 0,097	Moderate Density
NDBI ≥ 0,097	High Density

Source: modified from (Isnaeni and Prasetyo, 2021).

2.3.4. Surface Temperature and Energy Balance

LST was derived from radiometrically and atmospherically corrected Landsat 9 thermal bands. UTFVI was then applied to evaluate ecological conditions, as it reflects the deviation of surface thermal characteristics from the mean city temperature (Isnaeni and Prasetyo, 2021; Sameh et al., 2022; Sholihah et al., 2023). The mean surface temperature (Ts_{mean}) used in the calculation was obtained by averaging all pixels across both Jakarta and Semarang City. This approach provides a

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standardized comparison basis and minimizes inter-city bias when assessing deviations from thermal conditions. UTFVI was computed as:

$$UTFVI = \frac{Ts - Tsmean}{Tsmean} \quad (8)$$

where Ts is the surface temperature of a pixel (K) and Ts_{mean} is the mean surface temperature of the entire city (K). High values of LST and UTFVI indicate thermal stress and poorer ecological quality, whereas lower values reflect relatively cooler areas with better ecological conditions (Table 5).

Table 5. Categories of ecological conditions and UHI existence based on UTFVI.

UTFVI	Ecological Condition	UHI Intensity	Interpretation
UTFVI < 0,000	Very Good	None	Ecologically stable
0,000 ≤ UTFVI < 0,005	Good	Weak	Healthy environment
0,005 ≤ UTFVI < 0,010	Normal	Moderate	Mild heat stress
0,010 ≤ UTFVI < 0,015	Poor	Strong	Significant heat stress
0,015 ≤ UTFVI < 0,020	Very Poor	Very Strong	Severe heat stress
UTFVI ≥ 0,020	Extremely Poor	Extremely Strong	Critical heat stress

Source: thresholds adopted from (Hadibasyir et al., 2020)

Estimation of surface energy balance terms was based on the SEBAL algorithm. Albedo (α) was derived from reflectance spectra, continue with net radiation (Rn) which is the difference between incoming short wave radiation (RsIn) and outgoing shortwave radiation (RsOut) and outgoing long wave radiation (RlOut). Soil heat flux (G) was determined as a fraction of net radiation, whereas sensible heat flux (H) was estimated by means of the Bowen ratio method. Latent heat flux (LE) was determined as the residual of the energy balance (Bastiaanssen, 2000; Wiweka, 2014). The general form of the energy balance equation is expressed as (Artikanur and June, 2019):

$$Rn = G + H + LE \quad (9)$$

2.3.5. Land Surface Temperature Validation

Due to limited access to in-situ thermal data, validation of Landsat-derived LST followed the approach of previous study, that focusing on spatial pattern comparison (Ali et al., 2017). MODIS MOD11A2.061 was used as reference because of its ability to cover the study areas consistently. Landsat LST was resampled from 100 m to 1000 m using bilinear interpolation to match MODIS resolution. The agreement between datasets was evaluated using the Pearson correlation coefficient (r), confirming the reliability of Landsat data for urban thermal analysis.

2.3.6. Statistical Analysis

The relationships among UTFVI, NDVI, and NDBI were analyzed using simple and multiple linear regression, with UTFVI as the dependent variable, NDVI as an ecological indicator, and NDBI as a proxy for urbanization (Isnaeni and Prasetyo, 2021). Prior to multiple regression, multicollinearity was tested using the VIF to ensure predictor independence (Sholihah et al., 2023).

Differences between Jakarta and Semarang City were evaluated utilising the Mann–Whitney U test, a non-parametric technique appropriate for spatially heterogeneous data and unequal sample sizes (Cantica et al., 2023). A corrected significance threshold (α = 0,007) was applied to minimize Type I error (Emerson, 2020). Topographic variation in Semarang City was not explicitly modeled but handled through the use of averaged multi-scene Landsat imagery and city-wide mean LST in UTFVI calculations, ensuring fair inter-city comparison.

3. Results and Disscussion

3.1. General Characteristic and Land Profile

3.1.1 Supervised Classification

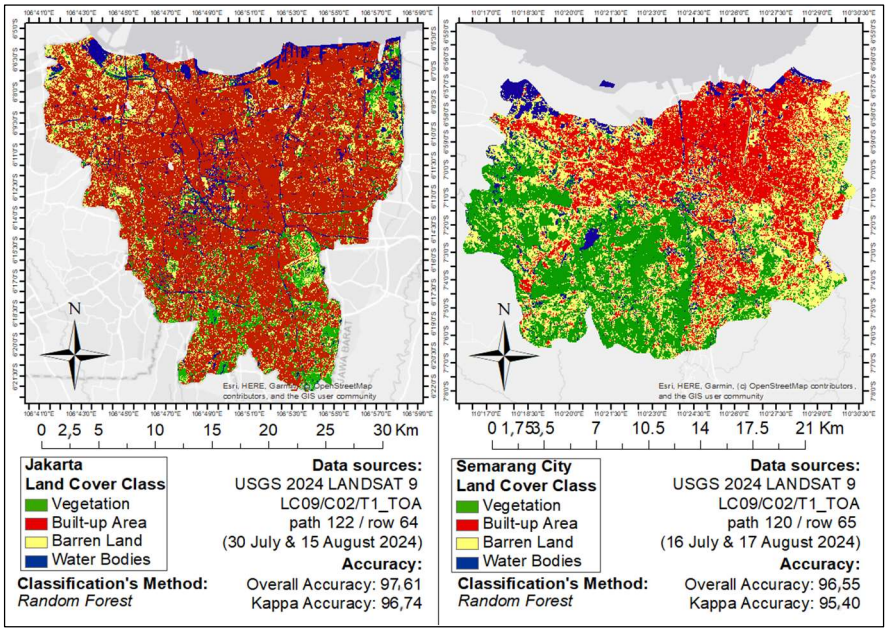
The supervised land cover classification in both regions achieved overall accuracy and kappa values exceeding 95% (Table 6). The accuracy of confusion matrix calculations for remote sensing must be at least 85% to be considered correct (Sampurno and Thoriq 2016). Jakarta's land cover was dominated by built-up areas (64,38%), and spatially, built-up areas are distributed across most parts of the city, while vegetation is observed in smaller and fragmented patches (Figure 3a). On the other hand, vegetated and open land areas are observed more widely in Semarang City, respectively, in its peripheral zones (Figure 3b). These results align with Wang et al. (2021), who mentions that built-up increment intensity directly reduces vegetation cover and subsequently enhances urban heat accumulation. Furthermore, the percentage distribution of land cover classes (Figure 4) suggests distinct differences between Jakarta and Semarang City, particularly in the proportion of built-up and vegetated area.

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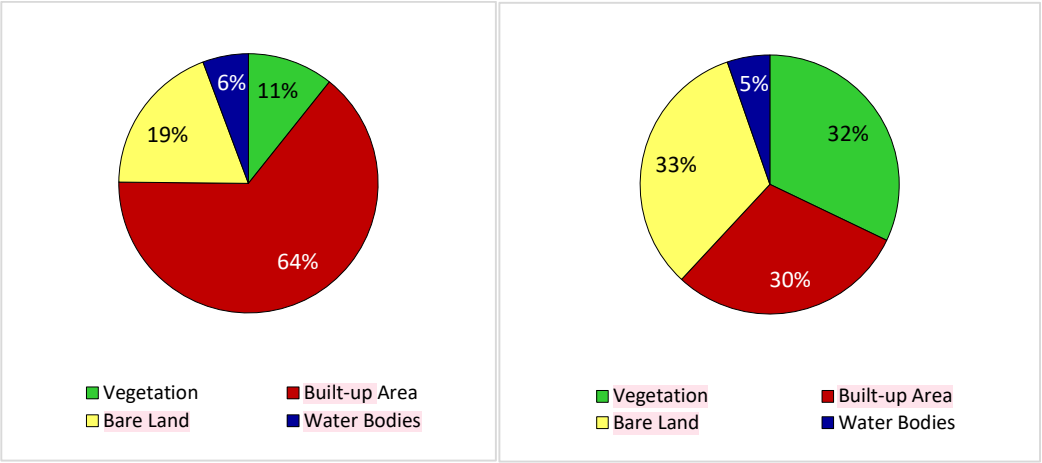
Table 6. Accuracy test values for land cover classification in both study areas.

Jakarta					
Sample (Training/Testing)	Class	Producer's Accuracy (%)	User's Accuracy (%)	Overall Accuracy (%)	Kappa Statistic
160/40	Water Body	100	100	97,61	0,9674
	Vegetation	100	87,50		
	Bare Soil	91,67	100		
	Built-up	100	100		
Semarang City					
Sample (Training/Testing)	Class	Producer's Accuracy	User's Accuracy	Overall Accuracy (%)	Kappa Statistic
124/31	Water Body	100	100	96,55	0,9540
	Vegetation	100	100		
	Bare Soil	100	87,50		
	Built-up	85,71	100		



(a) (b)

Figure 3. Supervised land cover classification results for (a) Jakarta and (b) Semarang City using the Random Forest algorithm based on Landsat 9 imagery (2024).



(a) (b)

Figure 4. Percentage distribution of land cover classes in (a) Jakarta and (b) Semarang City derived from Landsat 9 imagery (2024). Jakarta is dominated by built-up areas, whereas Semarang City shows a higher proportion of vegetation and open land, indicating differences in urbanization intensity.

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Vegetated areas that are relatively larger in Semarang could work as ecological buffers that lower temperature stress and maintain local environmental balance. However, if the city continues its urban growth without adequate preparation, especially to maintain effective conservation of its vegetated areas, it can lead to ecological degradation similar to that of Jakarta.

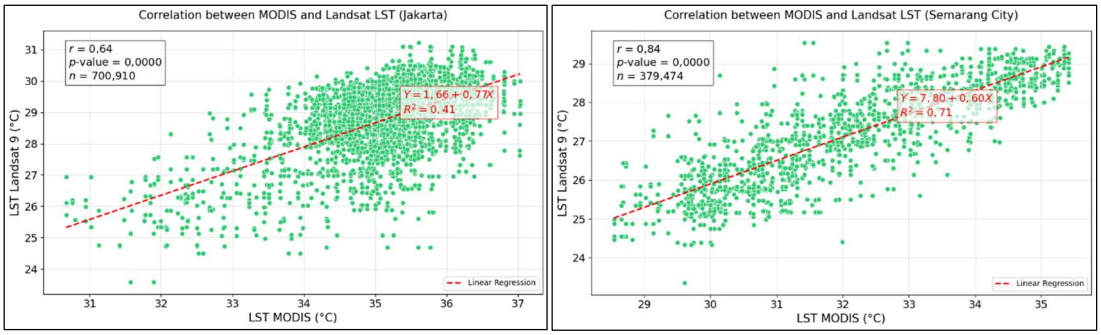
Another key point to consider is that extreme thermal environments caused by UHI can become a limiting factor for vegetation in tropical urban areas, which significantly affects both photosynthesis and transpiration processes (Kabano et al., 2021; Wang et al., 2021). In this context, it is quite concerning that Indonesia, as a developing tropical country, could become more vulnerable to challenges arising from uncontrolled urbanization and limited ecological management capacity.

3.1.2. Land Surface Temperature Validation

Figures 5a and 5b present correlation results of LST patterns from Landsat 9, which were resampled to a 1 km resolution to match the MODIS imagery. The estimated LST values from Landsat 9 ranged between 23–31 °C, while MODIS LST products ranged between 28–37 °C. The observed distinction in surface temperature ranges is likely to be a natural consequence of differences in sensor characteristics, retrieval algorithms, and acquisition times. Also, the MODIS imagery used in this study was composited from two 8-day scenes, whereas Landsat 9 utilized two single-date scenes.

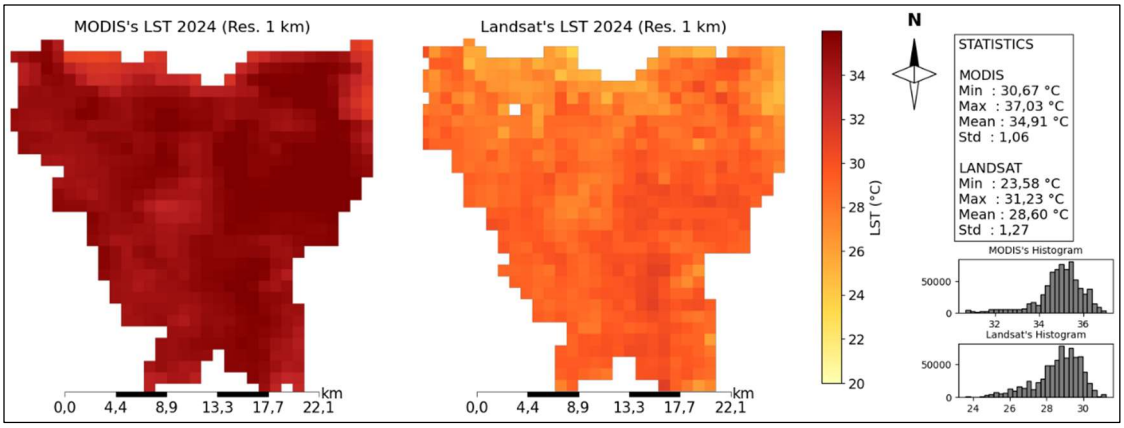
A similar deviation has been reported in a previous study, which emphasized that emissivity assumptions and sensor-specific calibration can lead to significant temperature differences (Simo et al., 2016). However, the study prioritized spatial pattern consistency rather than absolute temperature agreement, as the objective was to validate the spatial distribution of surface temperature rather than its temporal variability.

Despite these differences, Figure 6 and Figure 7 show that the land surface temperature patterns obtained from Landsat 9 and MODIS were generally consistent. The Pearson correlation coefficient was 0,71 for Jakarta and 0,93 for Semarang City, classified as strong and very strong correlations, respectively (Sugiyono, 2012).



(a) (b)

Figure 5. Correlation between MODIS LST (MOD11A2) and Landsat 9–derived land surface temperature (LST) for (a) Jakarta and (b) Semarang City. Landsat data were resampled to 1 km resolution to match MODIS, highlighting the consistency of spatial temperature patterns between sensors.



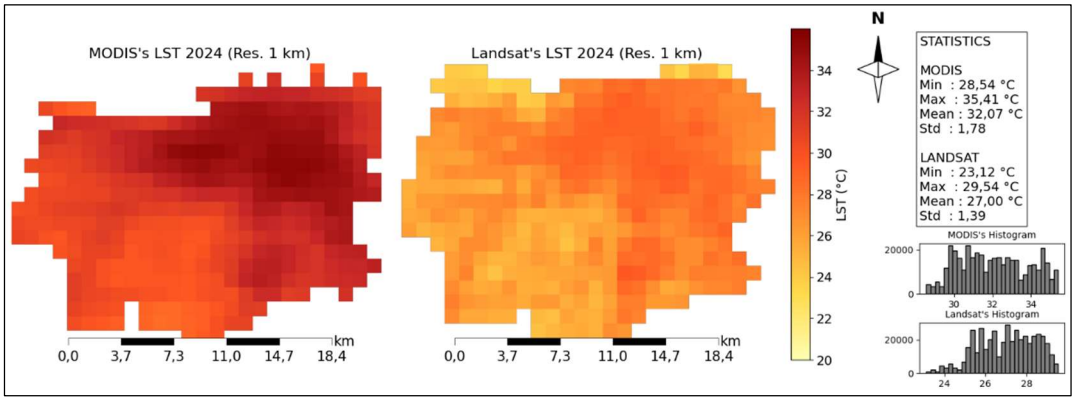
(a) (b)

Figure 6. Spatial distribution of land surface temperature (LST, °C) derived from (a) MODIS MOD11A2 and (b) Landsat 9 (resampled to 1 km) in Jakarta (2024). Despite differences in absolute temperature values, both datasets exhibit similar spatial distribution of thermal hotspots.

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Lugina, SM., and June, T. (2026). The Impact of Urbanization Scale on Ecological Conditions and Surface Heat Patterns: A Comparative Study of Jakarta – Semarang City. Jurnal Ilmu Lingkungan, xx(x), xx-xx, doi:10.14710/jil.xx.x.xxx-xx



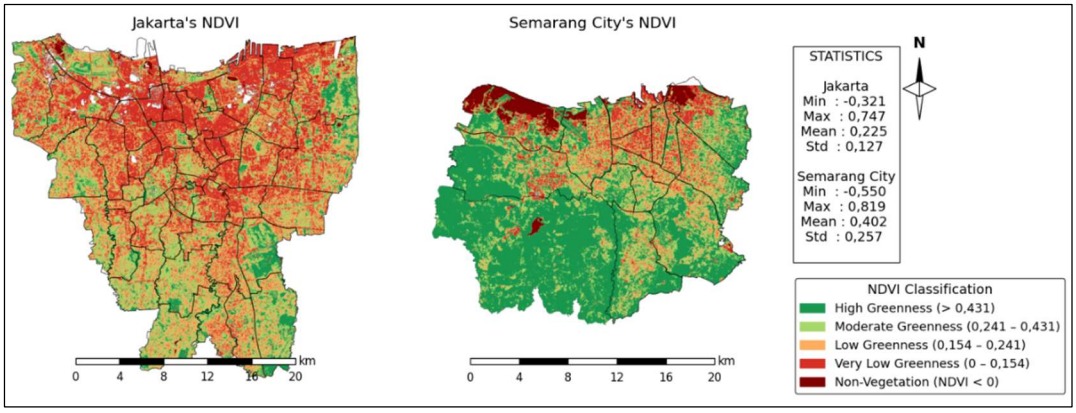
(a) (b)

Figure 7. Spatial distribution of land surface temperature (LST, °C) derived from (a) MODIS MOD11A2 and (b) Landsat 9 (resampled to 1 km) in Semarang City (2024).

3.2 Impact differences of urbanization scale on ecological condition

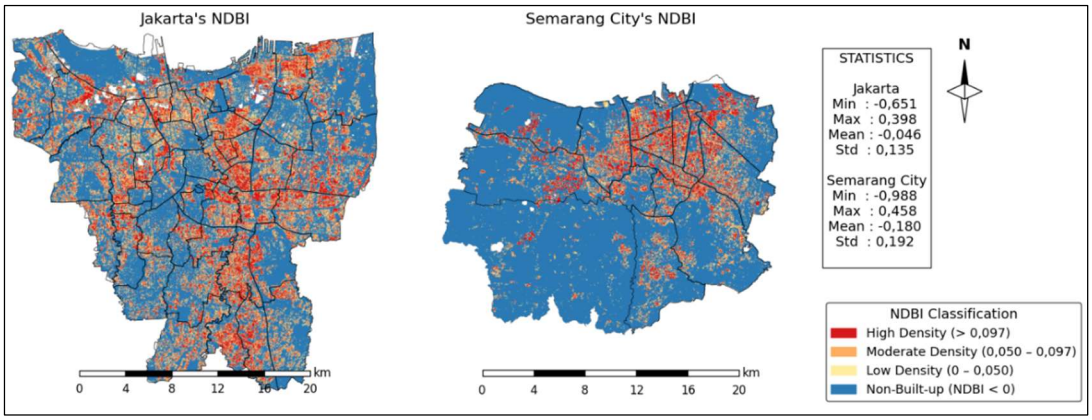
3.2.1. Spatial Patterns of Surface and Ecological Indicators

The significant differences in urbanization scale between Jakarta and Semarang City influenced the contribution of vegetation and built-up areas to urban ecological conditions. As shown in Figure 8 and Figure 9, respectively, NDVI and NDBI ranges in Jakarta (–0,32 to 0,75; –0,65 to 0,40) were narrower than those in Semarang City (–0,55 to 0,82; –0,99 to 0,46), indicating greater land cover variability in Semarang City. Additionally, the Mann–Whitney U test (Table 7) ensures that Jakarta has lower NDVI and higher NDBI values (P-value < 0,007), with effect sizes of r = –0,416 for NDVI and r = 0,378 for NDBI. This is supported in fact clear differences in vegetation and built-up index values between Jakarta and Semarang City.



(a) (b)

Figure 8. Spatial distribution of NDVI in (a) Jakarta and (b) Semarang City derived from Landsat 9 imagery (2024). Higher NDVI values in Semarang City reflect denser vegetation cover, while Jakarta exhibits limited and fragmented green areas.



(a) (b)

Figure 9. Spatial distribution of NDBI in (a) Jakarta and (b) Semarang City derived from Landsat 9 imagery (2024). Jakarta shows higher built-up intensity, indicating more extensive impervious surfaces compared to Semarang City.

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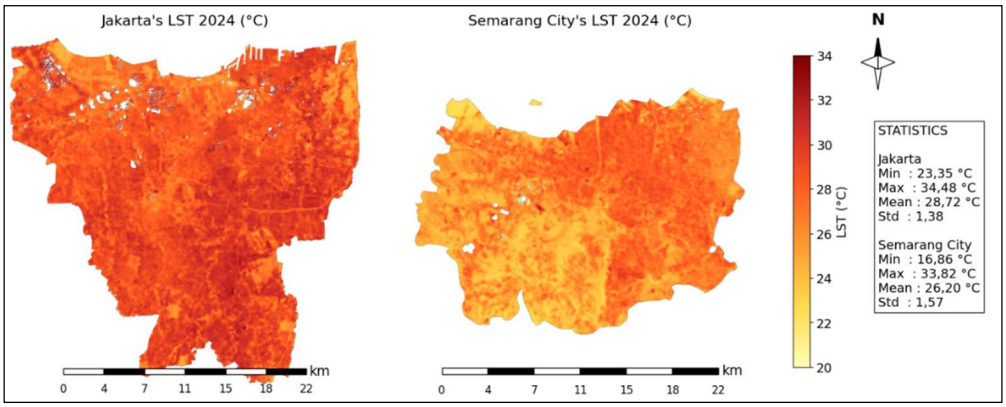
Table 7. Results of the Mann–Whitney U test comparing environmental variables between Jakarta (U1) and Semarang City (U2). All variables show statistically significant differences (p < adjusted α). Mean rank values indicate that Jakarta has higher UTFVI and NDBI, while Semarang City has higher NDVI.

Variable	U1	U2	Z	P-value	Adjusted α (Bonferroni)	Effect Size (r)	|r|	Jakarta's Mean Rank	Semarang City's Mean Rank
UTFVI	678	42	5,214	< 0,001	0,007	0,668	0,668	38,07	11,13
NDVI	162	558	-3,246	0,001	0,007	-0,416	0,416	26,60	43,38
NDBI	540	180	2,951	0,003	0,007	0,378	0,378	35,00	19,75

A two-tailed Mann–Whitney U test was conducted with Bonferroni correction for multiple comparisons (adjusted α = 0,007). Effect size (r) was calculated using the standardized Z statistic: $r = Z/\sqrt{N}$. Direction of difference was interpreted based on mean rank comparisons between groups.

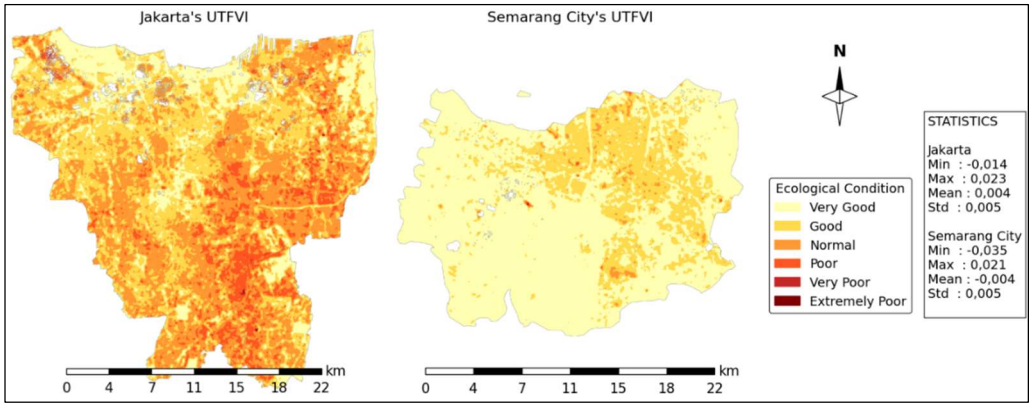
Cities with larger built-up areas usually experience higher temperatures because of the physical mechanisms of heat transfer. As shown in Figure 10, Jakarta has higher temperatures than Semarang City. Based on the UTFVI formula, the ecological condition reflects how much the surface temperature of a specific area deviates from the overall mean temperature. The lower Ts values than Tmean, the lower index value would become, which indicates a stable and healthy ecological condition typically associated with vegetated or open areas. On the contrary, higher Ts than its Tmean would make the index value increase, which reflects thermal stress and degraded ecological quality commonly found in densely built-up zones.

The UTFVI values were analyzed comparatively, as the mean surface temperature (Ts_{mean}) was derived from a combined dataset that reflects relative, not absolute ecological conditions. Therefore, the ecological condition interpreted from UTFVI in this study applies to the overall comparison between the two cities and does not represent a standalone local classification for each city. The difference in land surface temperature patterns between Jakarta and Semarang City (Figure 10) is observed to shape their ecological conditions, where higher and more concentrated heat in Jakarta shows a more degraded ecological condition, while Semarang City has cooler temperatures due to its vegetated areas, which maintain better ecological stability (Figure 11). As summarized in Table 8, Semarang City exhibited better ecological conditions, with 74,68% classified as very good, compared to 17,95% in Jakarta.



(a) (b)

Figure 10. Spatial distribution of land surface temperature (LST) in (a) Jakarta and (b) Semarang City during July–August 2024, showing higher temperatures in built-up areas and lower values in vegetated regions.



(a) (b)

Figure 11. Spatial patterns of the urban thermal field variance index (UTFVI) in (a) Jakarta and (b) Semarang City during July–August 2024, showing higher temperatures in built-up areas and lower values in vegetated regions.

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Table 8. Comparative ecological quality based on UTFVI values for Jakarta and Semarang City.

Category	Jakarta		Semarang City (%)	
	Precentage (%)	Total of Pixels (n)	Precentage (%)	Total of Pixels (n)
Very good	17,95	125011	74,68	299897
Good	34,80	242433	23,79	95541
Normal	38,89	270912	1,48	5934
Poor	8,28	57646	0,05	194
Very poor	0,08	536	0,01	25
Extremely poor	< 0,01	48	< 0,01	5
Total	100	696586	100	401596

These findings are supported by other studies, which also mentioned that high UTFVI values indicate significant thermal environmental degradation and are often associated with areas of low vegetation and dense built-up structures (Hadibasyir et al., 2020; Sameh et al., 2022). Denser built-up areas in Jakarta potentially decrease their ecological resilience, which shows how intensified urban development directly amplifies thermal stress and environmental vulnerability. This condition also makes cities more sensitive to worsening environmental pressures, as elevated temperatures and dense urban configurations can influence atmospheric processes related to urban air quality (Wangintan et al., 2024). For Semarang City, the better ecological quality suggests that mid-sized cities still possess opportunities to integrate sustainable planning before UHI effects intensify. This demonstrates the importance of proactive governance: ecological health declines disproportionately once urban density surpasses a critical threshold.

3.2.2. Statistical Analysis

The results of a simple linear regression analysis (Table 9) show that both vegetation (NDVI) and built-up area (NDBI) are significant predictors of the ecological condition index (UTFVI) in Jakarta and Semarang (p-value < 0,001). It also shows that increasing vegetation density is negatively correlated with UTFVI, while increasing built-up area density is positively correlated. Comparatively, NDBI explains more variation in UTFVI (R^2 NDBI > R^2 NDVI) in both cities. The NDVI in Semarang City has a slightly stronger correlation and contribution (Semarang City; r -0,580 and R2 0,345) than the NDVI in Jakarta (Jakarta; r -0,548 and R2 0,301). This indicates that vegetation in Semarang City has a stronger and more consistent effect on reducing surface heat than in Jakarta. On the other hand, the multiple regression results (p-value < 0,001; Table 10) show that NDBI contributes positively to the increase in UTFVI, with a higher coefficient in Jakarta (0,0225) than in Semarang City (0,0210). Conversely, NDVI contributes negatively, with a stronger effect in Semarang City (–0,0020) than in Jakarta (–0,0012). This finding confirms that the presence of buildings is more dominant in influencing thermal ecological conditions than vegetation, especially in megapolitan areas. Overall, the combination of NDVI and NDBI explains 55,3% of the variation in UTFVI in Jakarta and 57,3% in Semarang.

The results of both simple and multiple linear regression tests indicate that multiple urbanization worsens thermal ecological conditions more than vegetation mitigates them. These results match as well with previous studies, such as Zhao et al.'s (2020) study on the thermal contribution of land cover types in Beijing, which showed that the presence of buildings is indeed stronger in increasing temperatures than the presence of vegetation in reducing temperatures. Improving the quality of urban ecological conditions can be achieved by increasing vegetation and reducing the density of built-up areas (Hadibasyir and Firdaus 2022).

Table 9. Results of simple linear regression and Pearson correlation analysis of NDVI and NDBI in relation to UTFVI in Jakarta and Semarang City. R values and regression coefficients indicate a stronger positive association between built-up density and ecological stress than vegetation density in both cities.

Jakarta							
Variables	Model's Equation	Std. Error	P-value (t-test)	R^2	Sample Size (n)	F-statistic[b]	R (pearson)
NDVI	UTFVI = 0,0054 – 0,0124(NDVI)[a]	$2,87 \times 10^{-5}$	< 0,001	0,301	434.023	$1,87 \times 10^5$, p < 0,001	-0,548
NDBI	UTFVI = 0,0020 + 0,0239(NDBI)[a]	$3,22 \times 10^{-5}$	< 0,001	0,552		$5,34 \times 10^5$, p < 0,001	0,743
Semarang City							
Variables	Model's Equation	Std. Error	P-value (t-test)	R^2	Sample Size (n)	F-statistic[b]	R (pearson)
NDVI	UTFVI = 0,0061– 0,0139(NDVI)[a]	$3,1 \times 10^{-5}$	< 0,001	0,345	396.069	$2,01 \times 10^5$, p < 0,001	-0,580
NDBI	UTFVI = 0,0034 + 0,0228(NDBI)[a]	$3,15 \times 10^{-5}$	< 0,001	0,569		$5,24 \times 10^5$, p < 0,001	0,755

[a]All regression coefficients are statistically significant based on t-tests (p-value < 0,05; α = 0,05). [b]All regression models are statistically significant based on F-tests (p-value < 0,05; α = 0,05).

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Table 10. Multiple regression results of NDVI and NDBI on UTFVI, highlighting dominant built-up effects in Jakarta and vegetation cooling in Semarang.

Jakarta						
Variable	Coefficient	Std. Error	P-value (t-test)	R^2	Sample Size (n)	F-statistic[b]
Constant	0,0024[a]	$1,15 \times 10^{-5}$	< 0,001			
NDVI[c]	-0,0012[a]	$3,23 \times 10^{-5}$	< 0,001	0,553	434.023	$2,68 \times 10^{5}$, p < 0,001
NDBI[c]	0,0225[a]	$4,56 \times 10^{-5}$	< 0,001			
Semarang City						
Variable	Coefficient	Std. Error	P-value (t-test)	R^2	Sample Size (n)	F-statistic[b]
Constant	0,0040[a]	$1,28 \times 10^{-5}$	< 0,001			
NDVI[c]	-0,0020[a]	$3,55 \times 10^{-5}$	< 0,001	0,573	396.069	$2,66 \times 10^{5}$, p < 0,001
NDBI[c]	0,0210[a]	$4,48 \times 10^{-5}$	< 0,001			

[a]All regression coefficients are statistically significant based on t-tests ($p < 0,05$; $\alpha = 0.05$). [b]All regression models are statistically significant based on F-tests ($p < 0,05$; $\alpha = 0,05$). [c]NDVI and NDBI were tested for multicollinearity (Jakarta's VIF = 1,59; Semarang's VIF = 3,12).

3.3 Comparative Analysis of Surface Energy Balance Components

The Mann–Whitney test (Table 11) indicates significant differences in all energy balance components between Jakarta and Semarang, reflecting distinct surface energy exchange characteristics in the two cities. Figure 12 shows higher latent heat flux (LE) values in Semarang City, which indicate the strong role of vegetation in enhancing evapotranspiration and effectively reducing surface temperatures. Meanwhile, Jakarta's energy balance proportion is clearly dominated by sensible heat flux (H), which reflects limited vegetation cover and a higher amount of impervious surfaces with high thermal conductivity (Heisler and Brazel, 2010; Kara et al., 2025). The impervious surfaces are known for their ability to absorb and retain heat longer, then releasing it as sensible heat flux (H) and ground heat flux (G), both of which play a key role in the formation of the UHI effect. This pattern is consistent with previous regional climate modelling studies using the WRF framework, which reported that rapid land-use land-cover changes and extensive urban expansion have intensified the UHI effect in Jakarta (Sari et al., 2022).

Common urban materials such as concrete, asphalt, and bricks exhibit low albedo (<0,3) and high thermal admittance (Heisler and Brazel, 2010; Ihsan et al., 2022), increasing heat absorption and storage. Even if the use of high-albedo roofing materials (≥0,65) has been widely recommended for UHI mitigation (Sari et al., 2024; Wai et al., 2025), both Jakarta and Semarang City are still dominated by low-albedo surfaces (Figure 13), limiting their cooling potential. Therefore, approximately 70–80% of incoming solar energy is still retained, which makes heat transmission to the ground and atmosphere stronger.

Another key finding that can be observed is that there is a clear contrast between densely built-up areas that have high sensible heat flux (H) values and vegetated zones that are dominated by latent heat flux (LE) (Figure 14). Despite receiving higher net radiation (Rn), vegetated areas were observed to allocate more energy to latent heat fluxes (LE), thus reducing sensible heat (H) and ground heat (G) fluxes. This finding supports the principle that vegetation not only provides shading but also facilitates evapotranspirative cooling, playing a key role in maintaining surface energy balance and improving urban thermal conditions (Oke et al., 2017; Tan et al., 2021).

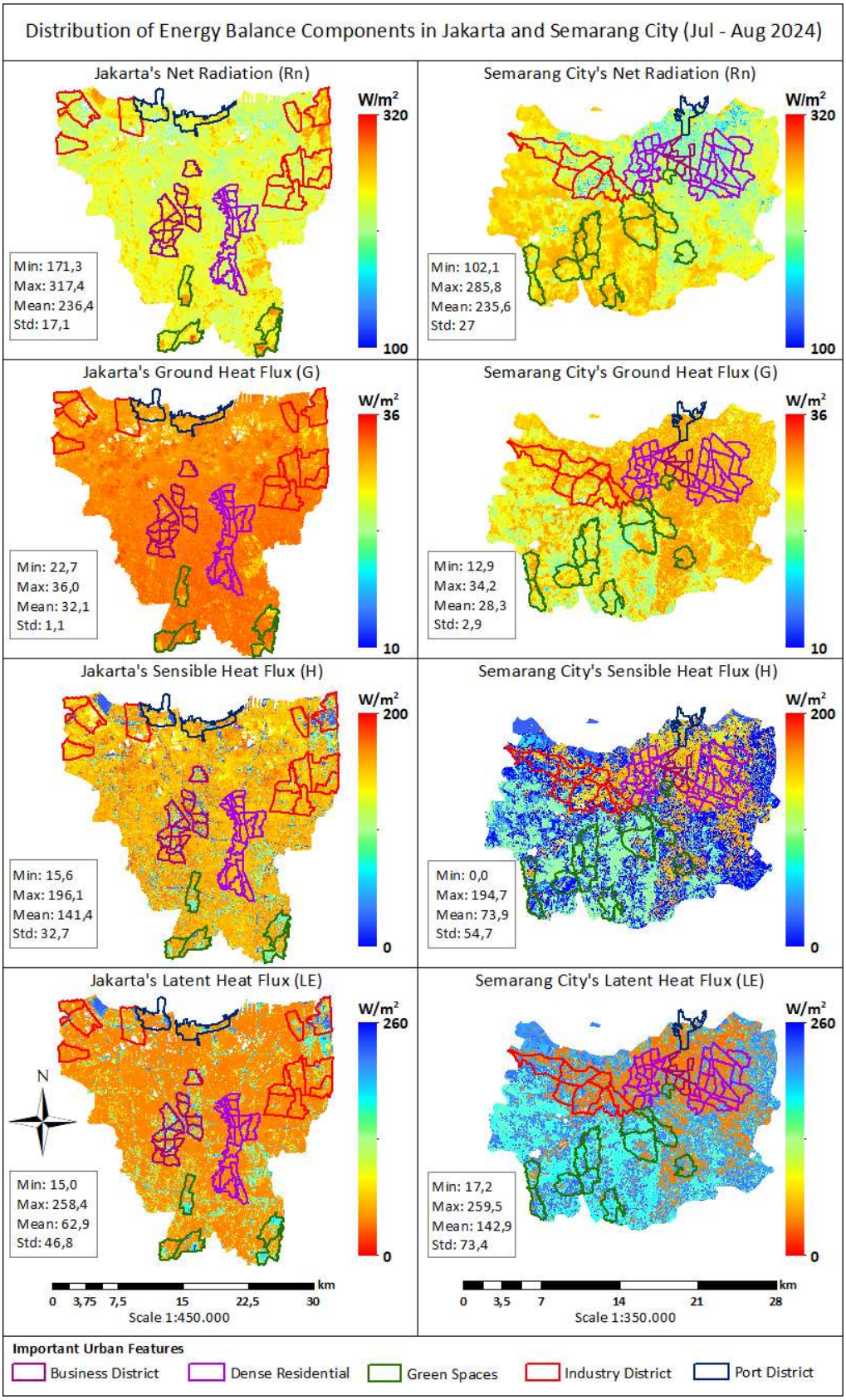
Table 11. Results of the Mann-Whitney difference test of energy balance components between Jakarta (U1) and Semarang City (U2). Significant differences (p < adjusted α) are observed across all components (Rn, G, H, and LE), indicating distinct surface energy exchange patterns between the two study areas. Mean rank values suggest Jakarta has higher Rn, G, and H, while Semarang City has higher LE.

Variable	U1	U2	Z	P-value	Adjusted α (Bonferroni)	Effect Size (r)	|r|	Jakarta's Mean Rank	Semarang City's Mean Rank
Rn	529	191	2,771	0,003	0,007	0,355	0,355	34,76	20,44
G	720	0	5,902	< 0,001	0,007	0,756	0,756	39	8,5
H	715	5	5,82	< 0,001	0,007	0,745	0,745	38,89	8,81
LE	47	673	-5,132	< 0,001	0,007	-0,657	0,657	24,04	50,56

A two-tailed Mann–Whitney U test was conducted with Bonferroni correction for multiple comparisons (adjusted α = 0,007). Effect size (r) was calculated using the standardized Z statistic: $r = Z/\sqrt{N}$. Direction of difference was interpreted based on mean rank comparisons between groups.

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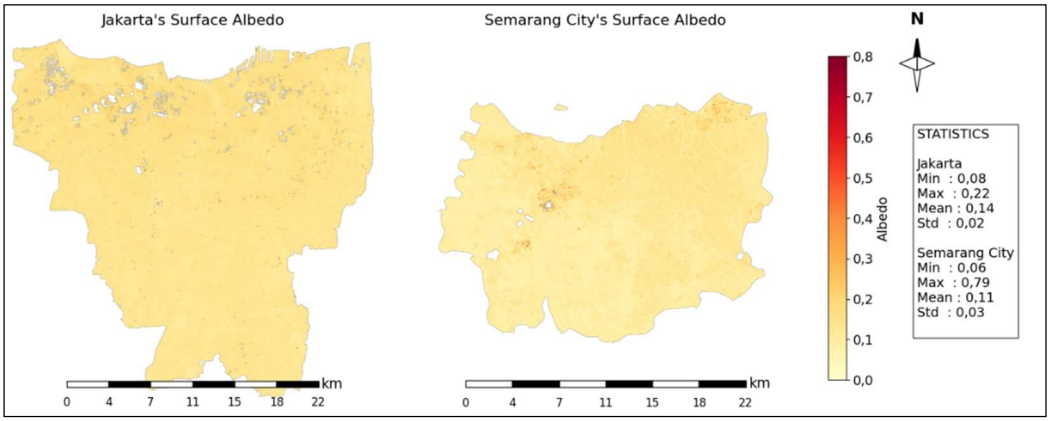


(a) (b)

Figure 12. Surface Energy balance components map Jakarta and Semarang City, respectively. The maps illustrate differences in net radiation (Rn), sensible heat flux (H), ground heat flux (G), and latent heat flux (LE), reflecting contrasting surface energy exchange mechanisms.

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(a) (b)

Figure 13. Surface albedo of (a) Jakarta and (b) Semarang City. Both cities are dominated by low-albedo built-up surfaces, which contribute to higher heat absorption and surface warming.

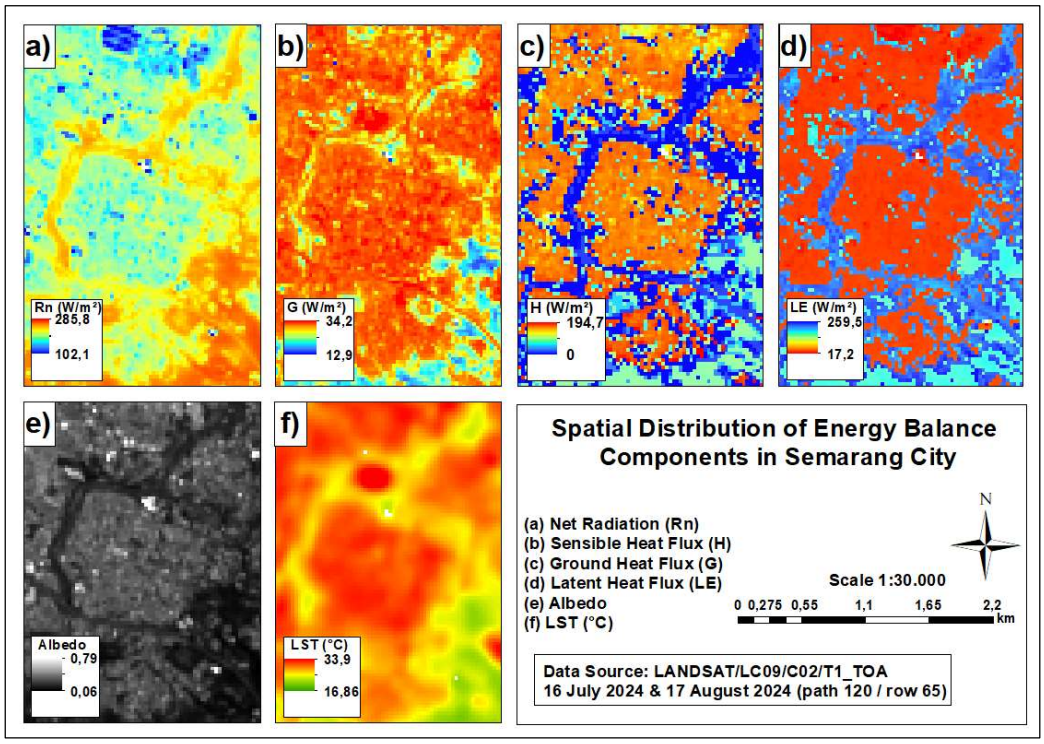


Figure 14. Details of energy balance components (a-d), (e) albedo, (f) LST, in Semarang City. Vegetated and less urbanized areas exhibit higher LE and lower H, indicating efficient energy dissipation through evapotranspiration. In contrast, densely built-up areas are characterized by lower albedo, higher sensible heat flux, and elevated surface temperatures, reflecting greater heat storage and reduced cooling capacity.

3.4 Limitation

Surface temperature validation was obtained through the data comparisons with MODIS imagery without direct field measurements. Though this is known as a common technical limitation in remote sensing studies, the differences in spatial resolution, image acquisition date, and image recording frequency, which were addressed through multi-scene averaging techniques, may not succeed in reflecting temporal variability. In addition, estimation of the energy balance components did not include the incoming longwave radiation due to data limitations and was assumed to be constant or relatively small under clear conditions. This could slightly lead to underestimates of the energy balance components. Despite these limitations, the spatial consistency between Landsat 9 and MODIS supports the robustness of the derived surface temperature patterns for further ecological and energy balance analyses.

3.5 Implication for Urban Planning and Mitigation

Jakarta has a residential proportion of 64,38% and a significantly higher NDBI value than Semarang. Energy partitioning in Jakarta is also dominated by the sensible heat flux (H = 141,41W/m^2) and has a higher ground heat flux than Semarang (G = 32,13W/m^2), with a very limited latent heat flux (LE) (62,88W/m^2). This reflects low evaporation and large amounts of energy stored and released, which would increase both surface and air temperatures. Due to its dense population and land

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limitations, these findings infer that mitigation strategies in Jakarta may prioritize vertical greening options, or may implement reflective coatings, cool pavements, and improved ventilation designs as well to reduce stored heat and enhance dissipation efficiency (Hadibasyir et al., 2020; Sari et al., 2024; Wai et al., 2025).

Meanwhile, a contrasting pattern is observed in Semarang City. It maintains lower surface temperatures (26,20 °C), higher NDVI, and greater latent heat flux (LE = 142,91 W/m^2), demonstrating that natural cooling through vegetation may remain effective. Therefore, urban management in Semarang City could prioritize conserving vegetated areas in the upland regions, particularly in Gunungpati and Mijen. This can be achieved by integrating NDVI and UTFVI indicators into spatial planning to help prevent ecological degradation (Darlina et al., 2018; Kumar et al., 2024). In addition, maintaining consistency between Rencana Tata Ruang Wilayah (RTRW), a regional spatial plan in Indonesia, and actual development is important to preserve the city's ecological balance. Without consistent enforcement of spatial plans, the city may gradually lose its natural cooling advantage, as reflected in its high latent heat flux.

4. Conclusion

The comparative analysis confirms that the scale of urbanization is a decisive factor shaping urban thermal patterns and ecological conditions. Jakarta's intense urbanization is associated with significantly higher land surface temperatures and widespread thermal stress, as evidenced by only about one-fifth of its area maintaining a "very good" category in the UTFVI compared to roughly three-quarters in Semarang City. This disparity is closely linked to land-cover differences: Jakarta's higher built-up intensity (higher NDBI) and reduced vegetation (lower NDVI) amplify heat accumulation and ecological degradation, whereas Semarang's more extensive vegetation cover helps sustain cooler surface temperatures and greater ecological stability through evapotranspiration. Indeed, built-up expansion emerged as the dominant driver of urban heat stress in Jakarta, whereas vegetation cover had a more pronounced cooling influence in Semarang's urban environment. The surface energy balance further highlights this contrast, with Jakarta's energy flux dominated by sensible heat (indicative of heat release from impervious surfaces) and Semarang's by latent heat (reflecting vigorous evaporative cooling from vegetated areas). These findings underscore the critical role of land cover composition, particularly the presence of vegetation, in enhancing urban ecological resilience and moderating UHI effects. Accordingly, urban heat mitigation strategies should be tailored to the scale of urbanization. In highly dense megacities like Jakarta, interventions such as vertical greening, reflective materials, and other engineered cooling designs are essential to offset the scarcity of green space. By contrast, in mid-sized cities like Semarang, protecting existing green spaces and integrating green–blue infrastructure into urban planning are key to preserving natural cooling functions and preventing future intensification of the UHI.

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