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COMPARATIVE ANALYSIS OF NDBI AND URBAN HEAT ISLAND ACROSS FIVE WALKABLE AREA TYPOLOGIES: EVIDENCE FROM JAKARTA

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ABSTRACT

Rapid urbanization in tropical megacities such as Jakarta has intensified land surface temperatures and altered microclimates, threatening pedestrian comfort and undermining efforts to create walkable urban environments. Despite the growing emphasis on walkability in sustainable urban design, limited evidence exists on how urban heat island (UHI) effects vary across different walkable area typologies, leaving planners without typology specific guidance for climate adaptive interventions. This study aims to compare the Normalized Difference Built-up Index (NDBI) and UHI intensity across five walkable area typologies in Jakarta, such as Koja, Salemba, Dukuh Atas, Pinang Ranti, and Pasar Minggu to examine how urbanization patterns shape thermal conditions and pedestrian comfort. Multitemporal Landsat imagery from 2014, 2019, and 2024 was used to quantify urbanization, vegetation cover (NDVI), land surface temperature (LST), and UHI intensity. Results indicate that Koja exhibits the highest NDBI, lowest NDVI, and greatest UHI, reflecting intense urbanization and significant vegetation loss. Pasar Minggu follows a similar but less extreme pattern, while Salemba and Pinang Ranti maintain moderate urbanization, higher vegetation cover, and lower UHI, supporting pedestrian thermal comfort. Dukuh Atas shows intermediate conditions, balancing urban density with preserved green space. A strong positive correlation between NDBI and UHI was confirmed, indicating that urban expansion exacerbates local heating, particularly in areas with limited vegetation. These findings highlight the importance of integrating green infrastructure and density management in urban planning to mitigate UHI and improve walkability, providing actionable, typology-specific insights for climate-adaptive urban design in tropical megacities and contributing to the achievement of Sustainable Development Goal 11.

Keywords: *Jakarta; normalized difference built-up index; urban heat island; walkability*

INTRODUCTION

The rapid pace of global urbanization has fundamentally altered surface energy balances and microclimatic conditions in cities, producing the well-documented urban heat island (UHI) phenomenon (Fajary et al., 2024). UHI is characterized by significantly higher air and surface temperatures within densely built environments compared with their peri-urban surroundings, and its intensity continues to grow under simultaneous urbanization and global warming pressures (Marks & Connell, 2024). In the Bangkok Metropolitan Region, surface UHI intensity rose from 4.40 oC in 2000 to 5.76 oC in 2020, illustrating how rapidly tropical megacities are warming (Pan et al., 2023). Heat exposure exacerbates heat-related mortality, cardiovascular stress, and reductions in outdoor mobility for vulnerable populations (Li et al., 2022). The phenomenon also displays strong intra-urban heterogeneity that closely tracks the proportion of impervious surfaces and green spaces, with significant projected impacts under future climate scenarios (Abdillah et al., 2025).

Jakarta exemplifies these dynamics with severity. Built-up areas in the city expanded by approximately 19% between 2000 and 2020, accompanied by considerable green-space loss and a measurable rise in surface temperature (Sarker et al., 2024). Three-decade intensity analyses reveal that built-up land has been an active gainer in nearly every five-year interval, with cropland and green areas serving as the primary suppliers of this expansion (Rachman et al., 2024). Urban-boundary-layer simulations between 1995 and 2014 indicate that the conversion of green to built-up classes alone increased Jakarta's air temperature by approximately 0.5 °C through reduced evapotranspiration (Maheng et al., 2024). Multitemporal satellite analyses confirm that the inner-city SUHI intensity in Jakarta now ranges between 1 °C and 2.5 °C and continues to rise (Siswanto et al., 2023). At the wider Java-island scale, the SUHI intensity in the Jakarta Metropolitan Area has approached 6 °C in the last decade, with land surface temperature increasing at an unchanged-pixel rate of 0.25 °C per year (Fajary et al., 2024). Local Indonesian studies have demonstrated that high urbanization and population density are directly proportional to UHI intensity across all five Jakarta administrative cities (Tulak et al., 2024). Furthermore, the absence of adequate urban green space significantly accelerates UHI formation in East Jakarta, particularly during the dry season (Rizki et al., 2024).

Among satellite-derived indicators, the Normalized Difference Built-up Index

(NDBI) remains one of the most reliable measures for delineating impervious surfaces from multispectral imagery, while NDVI captures vegetation cooling capacity (Sekertekin & Bonafoni, 2020). A robust positive correlation between NDBI and land surface temperature has been demonstrated repeatedly, with coefficients of determination frequently between 0.55 and 0.69 (Javaid et al., 2023). In contrast, NDVI exhibits a strong negative association with LST, supporting its use as a proxy for cooling capacity (Candraningtyas et al., 2025). In the South Jakarta context specifically, NDBI was identified as the strongest predictor of UHI variation among NDVI, NDWI, and NDBI, with a Pearson correlation coefficient of 0.55 (Putri et al., 2025). Multi-decadal indices-based assessments have consistently shown that the joint trajectory of rising NDBI and falling NDVI is the strongest predictor of UHI intensification across rapidly urbanizing tropical Indonesian landscapes (Agusman et al., 2025).

Concurrent with thermal concerns, walkability has emerged as a defining dimension of sustainable urbanism, capturing how density, diversity, design, destination accessibility, and distance to transit shape pedestrian environments (Ibrahim et al., 2024). In Indonesia, walkability has gained policy traction following the revitalization of Jakarta's Sudirman–Thamrin corridor, where pedestrian-oriented redesign improved walkability scores by approximately 39% and increased public-transport ridership by 15.41 % (Mulyadi et al., 2022). Walkable urban environments are not homogeneous; they exhibit distinct morphological typologies whose pedestrian experience varies sharply with compactness, building height, and street geometry (Kim, 2024).

A growing body of evidence shows that the thermal environment exerts a powerful influence on pedestrian behavior, especially in tropical cities. Studies in London demonstrate that integrating urban green systems and high-albedo pavements can lower pedestrian-level UHI by 0.5 °C to 2.5 °C under both current and future climate scenarios (Taher et al., 2024). Street-canyon geometry, asymmetric façades, and shading proportion further modulate microclimate at the pedestrian level (Hassan et al., 2024). Sidewalk-level heat-risk frameworks integrating microclimate modeling with pedestrian routing reveal that thermal stress can vary sharply within distances of less than

100 m (Colaninno et al., 2025). Whole-trip thermal-comfort evaluations underscore that the typology of the route, not just isolated features, ultimately determines walkability (Jia et al., 2024). Behavioral data from Hong Kong likewise show that pedestrians actively reroute to minimize cumulative heat exposure, even at the cost of additional travel distance (Chen et al., 2025).

Despite these advances, comparative analyses of NDBI and UHI across distinct walkable typologies remain rare in tropical megacity contexts (Li et al., 2022). Most Jakarta-focused thermal studies treat the metropolitan region as either a single unit or a coarse urban–rural gradient, neglecting the morphological diversity of pedestrian environments where exposure actually occurs (Sarker et al., 2024). Comparable Indonesian studies in Surabaya, Yogyakarta, and Bandung have examined city-wide LST–NDVI–NDBI dynamics without disaggregating by walkable typology (Candraningtyas et al., 2025). The absence of typology-stratified evidence limits planners' ability to prioritize cooling interventions where pedestrians are most vulnerable (Maheng et al., 2024). Integrating multitemporal Landsat-based NDBI, NDVI, LST, and UHI metrics for the years 2014, 2019, and 2024 offers a robust window into a decade of accelerating urbanization in Jakarta. This study therefore conducts a comparative analysis of NDBI and UHI across walkable typologies in Jakarta, representing variations in urban function, activity intensity, and pedestrian infrastructure conditions. The five areas, namely Salemba, Dukuh Atas, Koja, Pasar Minggu, and Pinang Ranti, were selected due to their distinct spatial and functional characteristics. Salemba represents an educational and commercial corridor with high pedestrian activity and infrastructure pressure. Dukuh Atas functions as a transit-oriented development area with strong transport integration but fluctuating pedestrian comfort during peak hours. Koja reflects a dense residential area with limited pedestrian facilities and high dependence on motorized transport. Pasar Minggu represents a peri-urban mixed-use area with heterogeneous mobility patterns that affect walkability consistency. Pinang Ranti serves as a transportation node with moderate integration but uneven pedestrian infrastructure quality. Although Jakarta continues to experience rapid urbanization and rising temperatures, these areas exhibit specific pedestrian issues such as unequal infrastructure quality, limited safety, and variations in environmental comfort. These conditions justify the need for a comparative analysis of walkability across different urban typologies to address spatial disparities in pedestrian environments. The outcomes contribute typology-specific empirical evidence for tropical climate-adaptive urban design, complement existing Jakarta-focused remote-sensing literature (Putri et al., 2025; Tulak et al., 2024), and align with global Sustainable Development Goal 11 of inclusive, safe, resilient, and sustainable cities (Rachman et al., 2024).

MATERIALS AND METHODS

1. Location and Time

This research employs a quantitative spatio-temporal analysis approach using multitemporal remote-sensing data. The study area covers the Special Capital Region of Jakarta (Sarker et al., 2024). Jakarta has a tropical monsoon climate with mean annual temperature of 27–32 °C and a pronounced dry season from May to September (Maheng et al., 2024). Within DKI Jakarta, five walkable area typologies were purposively selected to represent contrasting urban morphologies and pedestrian functions, spanning all five administrative cities of the province to ensure spatial representativeness across the metropolitan region (Tulak et al., 2024). The first typology is Koja, a port-adjacent dense residential corridor situated near Tanjung Priok Harbor. The second typology, Salemba, is an educational and medical district anchored by university and hospital complexes including the Universitas Indonesia Salemba campus and Cipto Mangunkusumo Hospital. The third typology, Dukuh Atas, represents Jakarta's flagship transit-oriented development (TOD) hub integrating MRT, LRT, KRL, and BRT services within a single pedestrian-accessible interchange. The fourth typology, Pinang Ranti, is a suburban transit node centered on the Pinang Ranti bus terminal and surrounded by mixed commercial–residential land use. The fifth typology, Pasar Minggu, constitutes a traditional market and high-density commercial corridor with long-established pedestrian activity adjacent to the Pasar Minggu commuter-rail station. All of the walkable areas as shown in **Figure 1** below.

This buffer using 700 m radial size was selected to maintain consistency across all five sites and to ensure that each delineated area falls within a comparable pedestrian catchment.

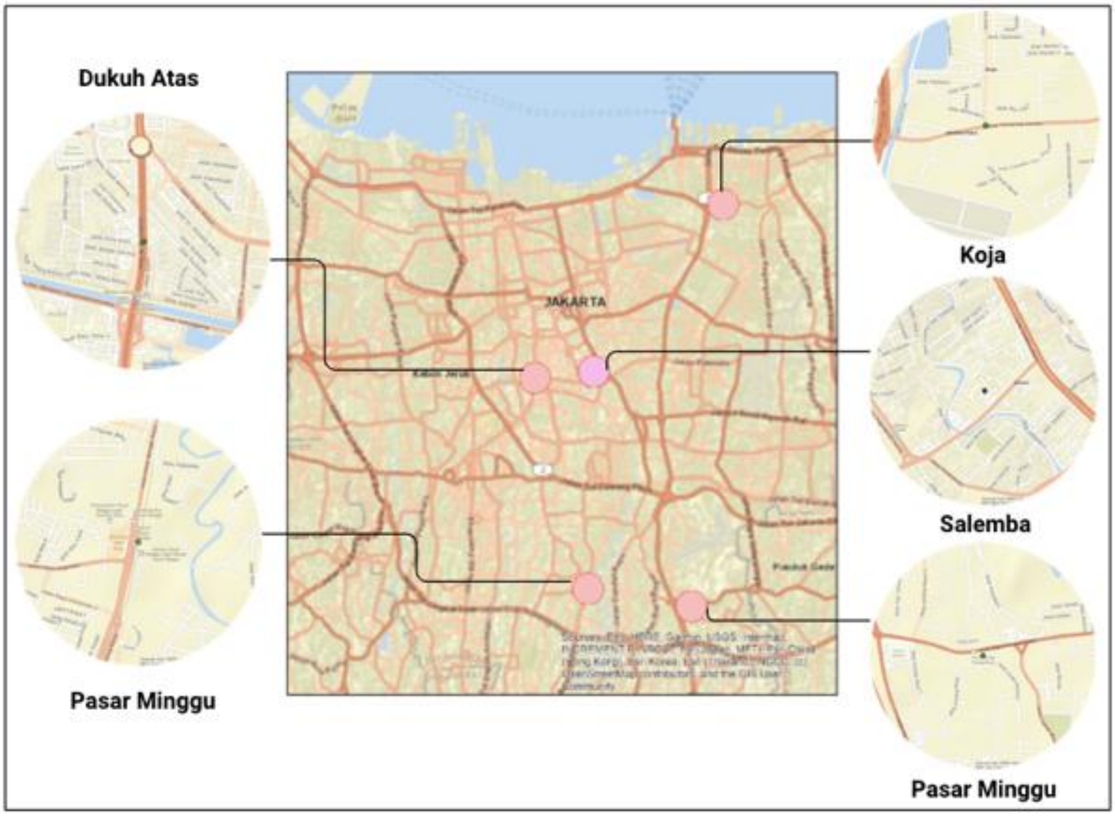

Figure 1. Location map of the five study areas in Jakarta, covering Dukuh Atas, Koja, Salemba, Pasar Minggu, and Pinang Ranti.

Source: Author’s data processing from OpenStreetMap using GIS, 2026

2. Materials

The principal materials used in this study consisted of multitemporal Landsat satellite imagery covering three observation years from 2014, 2019, and 2024. The imagery was obtained from Landsat-8 OLI/TIRS with Path 122 and Row 064 of the World Reference System-2 (WRS-2), covering the entire DKI Jakarta region. The data were acquired from the United States Geological Survey (USGS) Earth Explorer portal.

To ensure temporal consistency and minimize seasonal bias in NDVI, NDBI, LST, and UHI analysis, all images were selected from the dry season period in Jakarta and from comparable seasonal windows across years. The 2024 image was acquired on 31 August 2024 with cloud cover of 0.35%. The 2019 image was acquired on 25 July 2019 with cloud cover of 0.07%. The 2014 image was acquired on 28 August 2014 with cloud cover of 3.53%. All images were selected with low cloud contamination and clear atmospheric conditions to ensure reliable surface information extraction.

The use of dry season imagery is important because seasonal variation in rainfall and vegetation phenology can significantly influence NDVI, land surface temperature, and urban heat island intensity. By standardizing the acquisition period within the dry season, this study reduces seasonal variability and improves comparability across the three temporal datasets. This approach ensures that observed changes in NDVI, NDBI, LST, and UHI are primarily driven by urban land transformation rather than seasonal fluctuations.

3. Data Processing

All Landsat scenes underwent a sequential processing chain to derive the NDVI, NDBI, LST, and UHI from raw digital numbers. The imagery was first radiometrically calibrated into top-of-atmosphere (TOA) and spatial clipping to the DKI Jakarta administrative boundary as well as to the 700 m buffer of each walkable typology (Sekertekin & Bonafoni, 2020). NDVI was calculated using the near-infrared (NIR) and red bands of Landsat-8 OLI (Band 5 and Band 4). The calculation follows the normalized difference formula shown in equation 1.

$$NDVI = (NIR - Red)/(NIR + Red) \quad (1)$$

This index represents vegetation density and was used to measure spatial variation of green cover across all study areas (Candraningtyas et al., 2025).

NDBI was calculated using the short-wave infrared (SWIR) and near-infrared (NIR) bands of Landsat-8 OLI. The mathematical formulation is stated in equation 2.

$$NDBI = (SWIR-NIR)/(SWIR+NIR) \quad (2)$$

This index was used to identify and quantify built-up and impervious surface expansion (Putri et al., 2025).

Land surface temperature was retrieved using the Mono-Window Algorithm procedure consisting of five stages. First, Digital Number (DN) values from thermal Band 10 were converted into Top of Atmosphere (TOA) radiance. Second, radiance values were transformed into brightness temperature using thermal calibration constants K_1 = 774.8853 $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$ and K_2 = 1321.0789 K. Third, surface emissivity was estimated based on vegetation proportion derived from NDVI. Fourth, atmospheric correction parameters were applied using λ = 10.895 µm and ρ = 1.438 × 10^{-2} m·K. Finally, corrected brightness temperature was converted into Land Surface Temperature (LST) for each pixel (Sekertekin & Bonafoni, 2020).

UHI intensity in this study is defined operationally as the relative difference between land surface temperature in urban pixels and the mean reference temperature within the study area buffer. This is expressed in equation 3.

$$UHI = LST\ pixel - LST\_mean \quad (3)$$

Based on this definition, UHI values were classified into four categories:

a. < 0°C (cooler than reference)

b. 0–2°C (low intensity UHI)

c. 2–4°C (moderate intensity UHI)

This classification was applied pixel-wise to capture spatial variation of thermal stress across the five walkable typologies.

The four resulting indicators were aggregated at the typology level using zonal statistics within the 700 m buffer for each study area and for all observation years (2014, 2019, and 2024), producing a consistent dataset for comparative spatio-temporal analysis

RESULTS AND DISCUSSION

The NDVI distribution reflects strong differentiation based on urban functional morphology across the five typologies in Jakarta. Koja is characterized as a port-adjacent high-density residential and logistics corridor influenced by Tanjung Priok economic activities, warehousing systems, and informal settlements. This land-use structure leads to continuous vegetation removal and limited green space regeneration. Salemba functions as an educational and medical district dominated by university campuses and large hospital complexes, which preserve scattered green infrastructure within institutional land parcels. Dukuh Atas represents a Transit-Oriented Development (TOD) hub integrating MRT, LRT, KRL, and BRT systems, resulting in high built-form concentration but with residual linear vegetation along transport corridors. Pinang Ranti represents a suburban transit node with mixed residential-commercial land use and relatively lower development pressure. Pasar Minggu functions as a traditional market and commercial corridor with long-established economic activity that drives gradual land sealing and vegetation fragmentation.

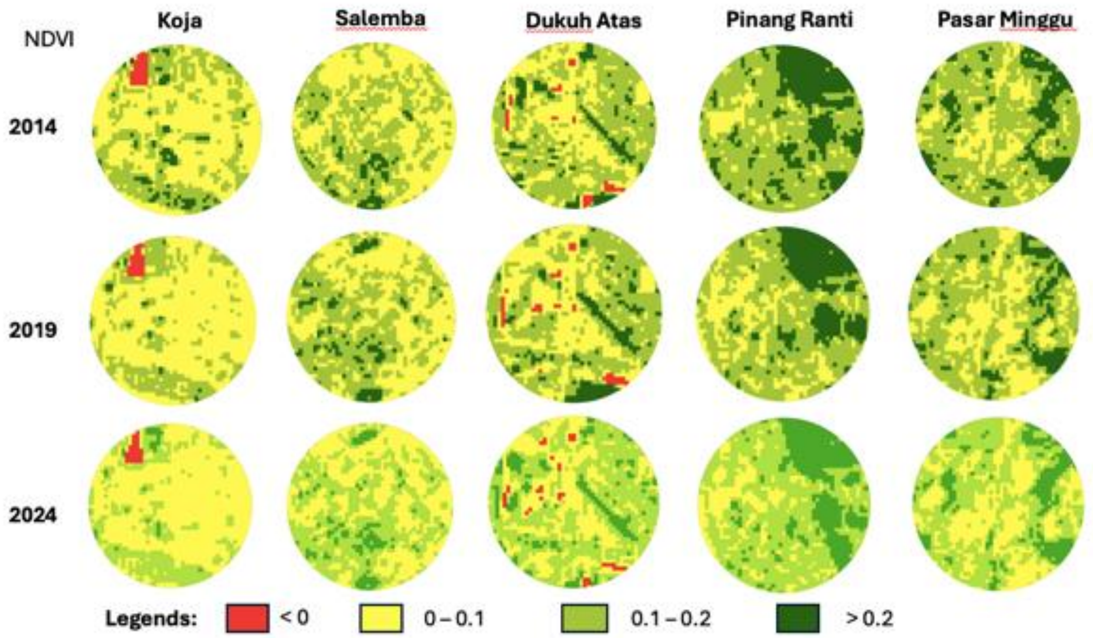

Figure 2. Spatial distribution of NDVI across study areas (Koja, Salemba, Dukuh Atas, Pinang Ranti, and Pasar Minggu) for the years 2014, 2019, and 2024.
Source: Author's data processing using GIS (2026)

Figure 2 illustrates the spatial and temporal distribution of NDVI across 2014, 2019, and 2024. Koja shows a consistent decline in vegetation cover, particularly in areas undergoing port-related expansion and residential densification, indicating progressive ecological degradation. Pasar Minggu exhibits a steady reduction in NDVI along commercial corridors where market expansion and roadside development intensify land conversion. Dukuh Atas demonstrates fragmented vegetation patterns typical of TOD environments, where transport infrastructure creates discontinuous green patches but still allows linear vegetation along pedestrian and transit routes. Salemba and Pinang Ranti maintain relatively stable NDVI conditions due to institutional land protection and suburban spatial structure. These results are consistent with Li et al. (2022), who found that vegetation decline in tropical megacities is strongly associated with logistics and commercial intensification, while institutional areas show higher ecological persistence.

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From an SDG 11 perspective, Koja and Pasar Minggu demonstrate weaker alignment with Target 11.7 due to limited accessibility and continuity of urban green space.

Table 1. Spatial distribution of NDVI classes across study areas (Salemba, Pasar Minggu, Koja, Dukuh Atas, and Pinang Ranti) for the years 2014, 2019, and 2024 based on area (Ha).

City	Class	Area (Ha)		
		2014	2019	2024
Salemba	< 0	N/A	N/A	N/A
	0 - 0.1	77,54	77,54	74,91
	0.1 - 0.2	68,33	68,33	67,74
	> 0.2	8,08	8,08	11,29
Pasar Minggu	< 0	N/A	N/A	N/A
	0 - 0.1	34,31	54,86	59,70
	0.1 - 0.2	91,42	80,39	71,98
	> 0.2	28,22	18,69	22,27
Koja	< 0	3,40	3,04	2,62
	0 - 0.1	89,85	110,35	109,75
	0.1 - 0.2	52,55	38,75	38,61
	> 0.2	8,15	1,81	2,98
Dukuh Atas	< 0	3,57	3,70	3,38
	0 - 0.1	59,00	62,17	59,13
	0.1 - 0.2	76,91	72,29	74,82
	> 0.2	14,46	15,78	16,62
Pinang Ranti	< 0	N/A	N/A	N/A
	0 - 0.1	16,76	37,75	31,39
	0.1 - 0.2	89,93	80,74	82,88
	> 0.2	47,27	35,46	39,68

Source: Author's data processing (2026)

Figure 3 presents the spatial evolution of NDBI from 2014 to 2024. Koja demonstrates continuous intensification of built-up surfaces, particularly in port-related logistics and residential zones, indicating strong land sealing dynamics. Dukuh Atas shows structured densification consistent with TOD principles, where transport infrastructure and commercial nodes concentrate spatial development vertically and horizontally. Pasar Minggu shows linear densification along market and commercial corridors, while Salemba and Pinang Ranti remain relatively stable due to controlled land-use transformation. These findings confirm that urban expansion in Jakarta is functionally driven and spatially clustered rather than uniformly distributed. This pattern aligns with Putri et al. (2025) and Javaid et al. (2023), who demonstrate a strong positive relationship between NDBI and surface temperature in rapidly urbanizing environments.

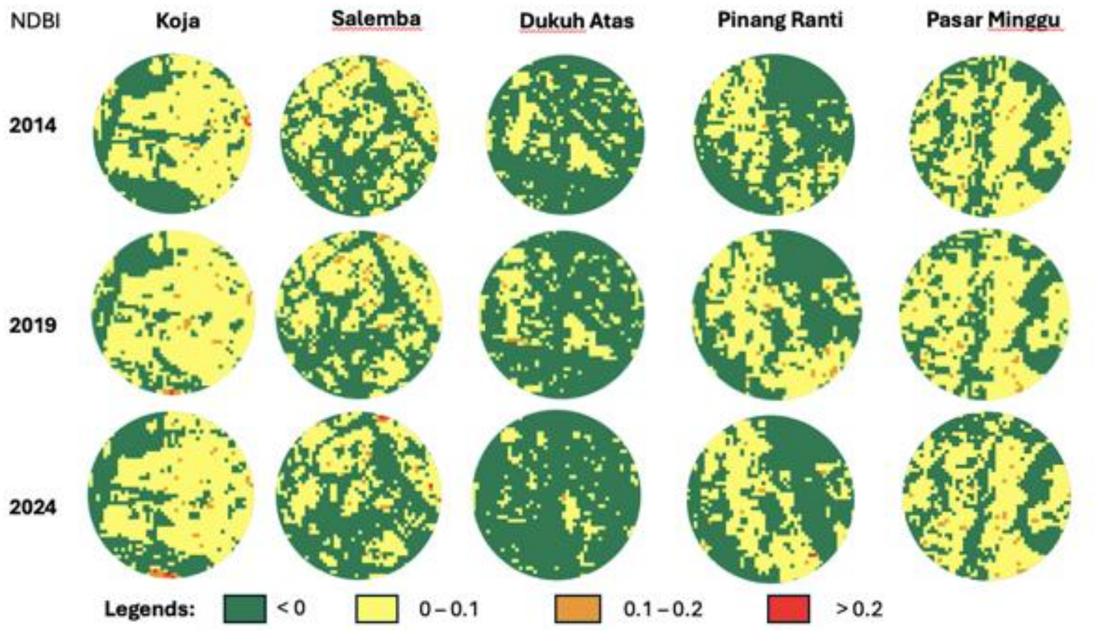

Figure 3. Spatial distribution of NDBI across study areas (Koja, Salemba, Dukuh Atas, Pinang Ranti, and Pasar Minggu) for the years 2014, 2019, and 2024.
Source: Author's data processing using GIS (2026)

Table 2 shows the distribution of NDBI classes across typologies, confirming differences in impervious surface concentration. Koja is dominated by moderate to high NDBI values, indicating strong built-up dominance. Dukuh Atas shows increasing NDBI distribution reflecting TOD-driven densification. Pasar Minggu presents moderate expansion of built-up areas, while Salemba and Pinang Ranti remain characterized by low NDBI classes, indicating more balanced spatial structure. These results strengthen the interpretation of **Figure 3** and confirm that impervious surface expansion is closely linked to functional urban roles.

The LST distribution reflects the combined effects of vegetation loss, surface sealing, and urban morphology. Koja exhibits the highest surface temperatures due to dense impervious surfaces and limited vegetation cover, particularly in logistics and residential clusters. Pasar Minggu shows elevated temperatures along commercial corridors where asphalt surfaces and limited shading increase heat absorption. Dukuh Atas exhibits spatially heterogeneous temperature patterns influenced by TOD infrastructure, where dense transport systems coexist with residual vegetation patches. Salemba and Pinang Ranti maintain relatively lower LST values due to institutional green coverage and suburban spatial structure.

Table 2. Spatial distribution of NDBI classes across study areas (Salemba, Pasar Minggu, Koja, Dukuh Atas, and Pinang Ranti) for the years 2014, 2019, and 2024 based on area (Ha).

City	Class	Area (Ha)		
		2014	2019	2024
Salemba	< 0	77,82	76,89	90,12
	0 - 0.1	73,87	74,27	61,10
	0.1 - 0.2	2,25	2,79	2,43
	> 0.2	N/A	N/A	0,29
Pasar Minggu	< 0	65,75	55,64	66,34
	0 - 0.1	87,00	95,59	85,16
	0.1 - 0.2	1,20	2,72	2,44
	> 0.2	N/A	N/A	N/A
Koja	< 0	57,37	41,10	55,41
	0 - 0.1	94,85	110,34	95,31
	0.1 - 0.2	1,56	2,37	2,90
	> 0.2	0,18	0,14	0,33
Dukuh Atas	< 0	116,16	115,81	134,63
	0 - 0.1	37,69	37,32	19,13
	0.1 - 0.2	0,09	0,81	0,18
	> 0.2	N/A	N/A	N/A
Pinang Ranti	< 0	98,88	80,03	92,18
	0 - 0.1	54,53	71,75	60,53
	0.1 - 0.2	0,54	2,17	1,07
	> 0.2	N/A	N/A	0,18

Source: Author's data processing (2026)

Figure 4 illustrates the spatial distribution of LST across the three observation years. Koja consistently shows persistent thermal hotspots concentrated in high-density built-up and logistics zones. Pasar Minggu exhibits linear heat accumulation along commercial corridors, reflecting strong anthropogenic heat influence. Dukuh Atas shows fragmented hotspots around transit infrastructure, indicating TOD-induced thermal variability. Salemba and

Pinang Ranti show relatively cooler surface conditions due to vegetation presence and lower surface sealing. These findings are consistent with Maheng et al. (2024) and Fajary et al. (2024), who highlight that urban land conversion produces highly heterogeneous thermal landscapes in tropical megacities.

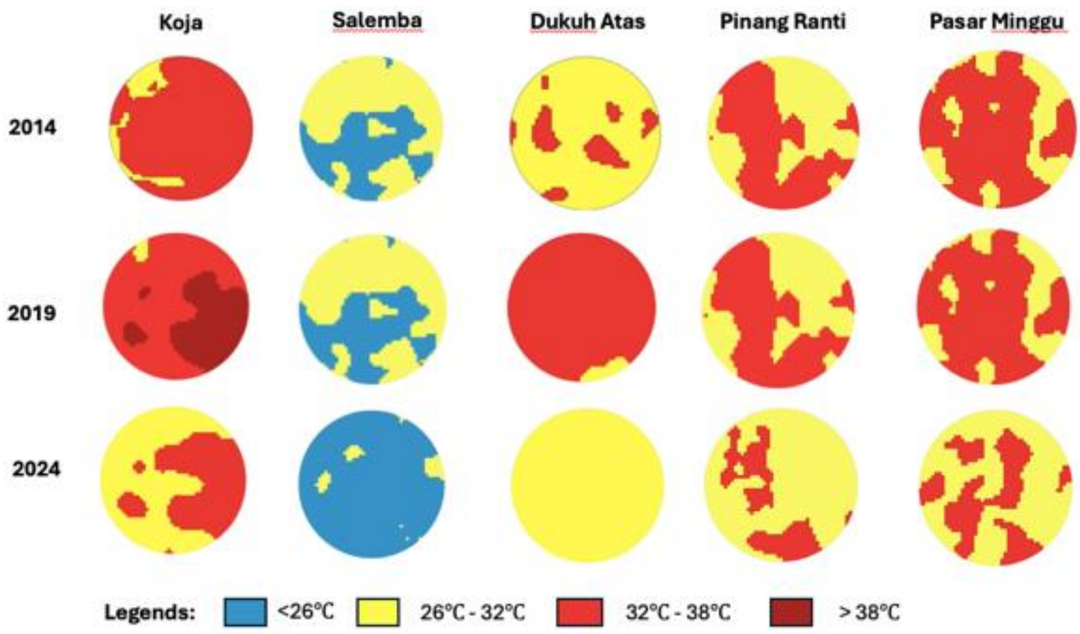

Figure 4. Spatial distribution of LST across study areas (Koja, Salemba, Dukuh Atas, Pinang Ranti, and Pasar Minggu) for the years 2014, 2019, and 2024.
Source: Author's data processing using GIS (2026)

Table 3 presents LST class distribution across typologies, confirming spatial thermal differences. Koja shows the highest proportion of high-temperature classes, indicating severe surface heating. Pasar Minggu shows moderate to high thermal classes along commercial corridors. Dukuh Atas exhibits mixed thermal distribution, while Salemba and Pinang Ranti are dominated by lower temperature classes. These results validate the spatial interpretation in Figure 4 and confirm the influence of land-use structure on thermal variability.

The UHI distribution reflects spatial thermal imbalance driven by land-use intensity and vegetation distribution. Koja experiences persistent urban heat stress due to dense built-up structures and limited ecological buffering. Pasar Minggu shows moderate UHI intensity along commercial corridors. Dukuh Atas exhibits mixed UHI conditions influenced by TOD infrastructure and partial vegetation retention. Salemba and Pinang Ranti show consistently low UHI intensity due to better ecological balance and lower impervious surface density.

Table 3. Spatial distribution of LST classes across study areas (Salemba, Pasar Minggu, Koja, Dukuh Atas, and Pinang Ranti) for the years 2014, 2019, and 2024 based on area (Ha).

City	Class	Area (Ha) LST		
		2014	2019	2024
Salemba	< 26 °C	59,22	N/A	146,39
	26 - 32 °C	94,64	151,33	7,56
	32 - 38 °C	0,08	2,61	N/A
	> 38°C	N/A	N/A	N/A
Pasar Minggu	< 26 °C	N/A	N/A	N/A
	26 - 32 °C	41,53	153,40	102,09
	32 - 38 °C	112,41	0,54	51,86
	> 38°C	N/A	N/A	N/A
Koja	< 26 °C	N/A	N/A	N/A
	26 - 32 °C	16,96	2,38	84,78
	32 - 38 °C	136,99	98,67	66,55
	> 38°C	N/A	52,90	N/A
Dukuh Atas	< 26 °C	N/A	N/A	137,29
	26 - 32 °C	131,64	5,31	13,27
	32 - 38 °C	22,30	148,63	N/A
	> 38°C	N/A	N/A	N/A
Pinang Ranti	< 26 °C	N/A	0,46	N/A
	26 - 32 °C	70,99	131,58	118,75
	32 - 38 °C	82,96	21,91	35,21
	> 38°C	N/A	N/A	N/A

Source: Author's data processing (2026)

Figure 5 presents the spatial distribution of UHI intensity across the study period. Koja shows persistent hotspot clusters in dense residential and logistics areas. Pasar Minggu shows linear UHI patterns along commercial corridors, reflecting continuous anthropogenic heat accumulation. Dukuh Atas shows fragmented UHI distribution influenced by TOD infrastructure and mixed land use. Salemba and Pinang Ranti demonstrate stable low UHI conditions due to vegetation presence and controlled urban development. These findings align with Chen et al. (2025) and Colaninno et al. (2025), who emphasize that micro-scale urban morphology strongly determines pedestrian thermal exposure.

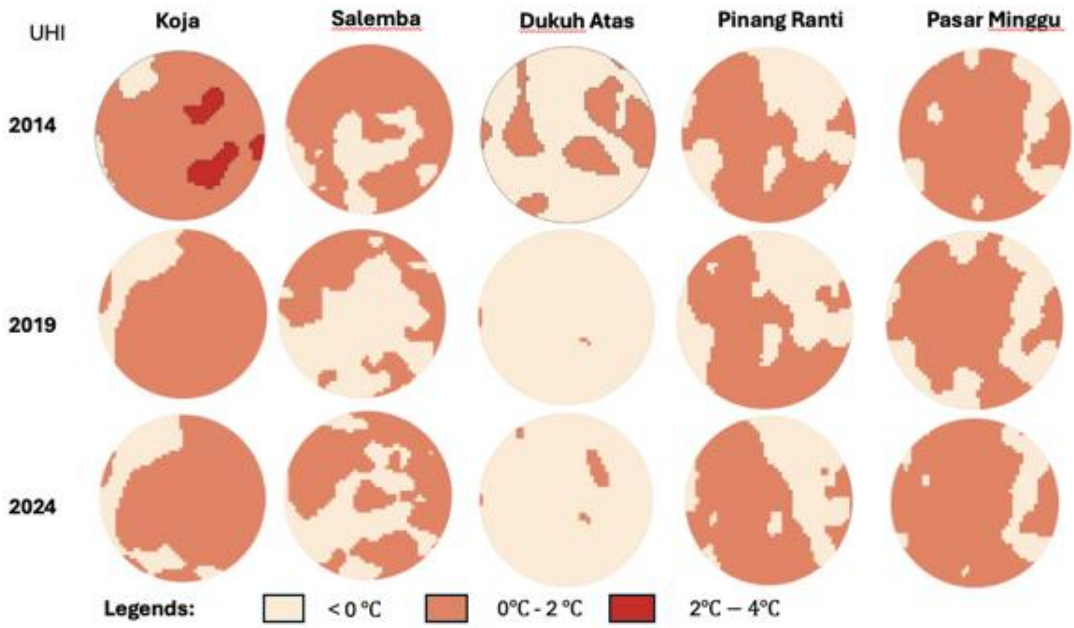

Figure 5. Spatial distribution of UHI across study areas (Koja, Salemba, Dukuh Atas, Pinang Ranti, and Pasar Minggu) for the years 2014, 2019, and 2024.
Source: Author's data processing using GIS (2026)

Table 4 shows UHI class distribution across typologies, confirming spatial variation in thermal stress. Koja exhibits the highest proportion of moderate UHI classes, indicating sustained heat exposure. Pasar Minggu shows moderate UHI distribution along commercial corridors. Dukuh Atas shows mixed thermal conditions, while Salemba and Pinang Ranti remain dominated by low UHI classes. These quantitative results support Figure 5 and confirm that urban heat intensity is strongly linked to land-use structure and vegetation availability.

The integrated analysis of NDVI, NDBI, LST, and UHI confirms a consistent spatio-temporal relationship across all typologies. Koja represents the most critical condition where high built-up intensity and low vegetation cover jointly drive elevated surface temperature and UHI intensity. Salemba and Pinang Ranti represent more balanced urban environments with stable vegetation and lower thermal stress. Dukuh Atas represents a transitional TOD typology where densification is partially offset by structured spatial planning and residual green infrastructure. Pasar Minggu occupies an intermediate position characterized by gradual thermal accumulation along commercial corridors. These findings confirm that urban heat dynamics in Jakarta are primarily driven by land-use transitions and functional spatial structure rather than uniform urban expansion, consistent with Sarker et al., (2024) and Rachman et al. (2024).

Table 4. Spatial distribution of UHI classes across study areas (Salemba, Pasar Minggu, Koja, Dukuh Atas, and Pinang Ranti) for the years 2014, 2019, and 2024 based on area (Ha).

City	Class	Area (Ha) UHI		
		2014	2019	2024
Salemba	< 0	38,90	88,89	60,07
	0 - 2 °C	115,05	64,97	93,87
	2 - 4 °C	N/A	N/A	N/A
	> 4 °C	N/A	N/A	N/A
Pasar Minggu	< 0	29,13	51,00	25,38
	0 - 2 °C	124,82	102,94	128,57
	2 - 4 °C	N/A	N/A	N/A
	> 4 °C	N/A	N/A	N/A
Koja	< 0	9,50	24,99	33,84
	0 - 2 °C	128,66	128,96	116,85
	2 - 4 °C	15,79	N/A	0,64
	> 4 °C	N/A	N/A	N/A
Dukuh Atas	< 0	110,55	153,29	142,08
	0 - 2 °C	43,39	0,65	8,48
	2 - 4 °C	N/A	N/A	N/A
	> 4 °C	N/A	N/A	N/A
Pinang Ranti	< 0	60,12	61,96	55,12
	0 - 2 °C	93,83	92,00	98,83
	2 - 4 °C	N/A	N/A	N/A
	> 4 °C	N/A	N/A	N/A

Source: Author’s data processing (2026)

The discussion of urban thermal patterns in this study extends beyond class distribution by examining spatial hotspot formation and the underlying drivers of variability across different urban typologies. The results indicate that UHI intensity is not randomly distributed but concentrated in specific functional zones, particularly in areas characterized by high building density, limited vegetation, and intensive anthropogenic activity. Koja consistently emerges as the dominant hotspot area due to its role as a port-adjacent logistics and dense residential zone. The combination of industrial-support activities, heavy transportation movement, and continuous land sealing creates persistent thermal accumulation zones. Pasar Minggu also shows notable hotspot formation along commercial corridors where market activities and roadside development increase surface heat retention.

Dukuh Atas exhibits a different thermal structure compared to Koja and Pasar Minggu. As a Transit-Oriented Development (TOD) area, its hotspots are fragmented and primarily concentrated around transport infrastructure nodes such as MRT and LRT interchange zones. This pattern reflects high built-up density but also partial mitigation effects from shaded pedestrian infrastructure and remaining vegetation patches. In contrast, Salemba and Pinang Ranti show weak hotspot intensity due to the presence of institutional land use and suburban spatial structure, which still allows vegetation retention and reduces surface heat accumulation.

These spatial differences indicate that urban heat island formation is strongly controlled by land-use function rather than administrative boundaries. Port areas generate continuous heat due to logistics intensity, TOD areas produce fragmented heat due to infrastructure concentration, and commercial corridors generate linear heat patterns following economic activity routes. Similar findings were reported by Chen et al. (2025), who identified that pedestrian-level thermal stress in dense urban environments is strongly influenced by movement corridors and built-form configuration. Colaninno et al. (2025) also emphasized that micro-scale urban morphology can significantly alter heat exposure even within short spatial distances, which is consistent with the hotspot variability observed in this study.

The variation in UHI intensity across typologies is primarily driven by three interacting factors: built-up density (NDBI), vegetation cover (NDVI), and urban functional specialization. Koja represents the most critical case where high NDBI and low NDVI jointly intensify surface heating. Pasar Minggu reflects moderate thermal stress driven by continuous commercial activity and reduced vegetation buffering. Dukuh Atas demonstrates a transitional thermal condition where TOD-based densification is partially offset by structured spatial planning and residual green infrastructure. Salemba and Pinang Ranti represent relatively stable thermal environments due to institutional land use and suburban morphology that maintain ecological balance.

From a sustainability perspective, these findings have direct implications for SDG 11, particularly Target 11.7 and Target 11.6. Areas with strong hotspot concentration such as Koja and Pasar Minggu indicate reduced accessibility to thermally comfortable public spaces, which limits pedestrian activity and weakens urban inclusiveness. In contrast, Salemba and Pinang Ranti demonstrate better alignment with SDG 11 due to lower heat exposure and more balanced land-use composition, which supports safer and more comfortable pedestrian environments. Dukuh Atas shows partial alignment, where TOD development improves accessibility but still requires stronger integration of green infrastructure to mitigate thermal stress.

When compared with previous studies, the findings of this research are consistent with Maheng et al. (2024), who reported that land-use change in Jakarta significantly increases surface temperature and creates spatially heterogeneous heat patterns. Fajary et al. (2024) also confirmed that urban thermal dynamics in tropical megacities are strongly linked to impervious surface expansion and vegetation loss. However, this study extends previous findings by providing a typology-based comparison, demonstrating that thermal risk is not only determined by urban expansion but also by specific functional roles such as ports, TOD hubs, markets, and institutional zones.

Overall, the discussion confirms that urban heat in Jakarta is structurally embedded in land-use organization. The spatial concentration of hotspots in Koja and Pasar Minggu highlights the vulnerability of logistics and commercial corridors, while the relatively stable conditions in Salemba and Pinang Ranti indicate the importance of institutional and suburban green structures in mitigating urban heat. This typology-based evidence provides actionable insights for climate-responsive urban planning, particularly in strengthening green infrastructure integration within high-density urban and TOD environments.

CONCLUSIONS

The comparative analysis of five walkable typologies in Jakarta reveals clear spatial disparities in vegetation cover, built-up intensity, land surface temperature, and urban heat island (UHI) effects. Each typology demonstrates distinct thermal and ecological characteristics shaped by its dominant urban function. Koja, as a port-adjacent logistics and high-density residential area, consistently exhibits the lowest NDVI, highest NDBI, and strongest UHI intensity, indicating the most severe environmental stress among all typologies. Pasar Minggu, as a traditional market and commercial corridor, shows similar but less extreme conditions characterized by gradual vegetation loss and increasing thermal accumulation. Dukuh Atas, as a Transit-Oriented Development (TOD) hub, presents a transitional pattern where high urban density is partially mitigated by structured spatial design and residual green infrastructure. In contrast, Salemba and Pinang Ranti demonstrate more balanced conditions with relatively stable vegetation cover, lower built-up intensity, and lower thermal stress due to institutional and suburban land-use structures.

Over the ten-year observation period (2014–2024), all indicators show a consistent temporal trend. NDVI values generally decline across all typologies, particularly in Koja and Pasar Minggu, indicating progressive vegetation loss. In contrast, NDBI and LST values increase in highly urbanized areas, reflecting continuous expansion of impervious surfaces and rising surface temperature. UHI intensity also strengthens over time in Koja and Pasar Minggu, while Salemba and Pinang Ranti remain relatively stable with lower thermal variation. Dukuh Atas shows moderate fluctuations, reflecting the dynamic balance between densification and urban design interventions associated with TOD development. These trends confirm that urban thermal conditions in Jakarta are increasingly shaped by land-use transformation and functional urban specialization.

The findings contribute directly to Sustainable Development Goal 11 (SDG 11), particularly Target 11.7 and Target 11.6, by demonstrating how unequal spatial distribution of vegetation and urban density affects pedestrian thermal comfort and access to safe, inclusive public spaces. Areas with high UHI intensity such as Koja and Pasar Minggu indicate lower levels of environmental livability and reduced walkability conditions, while Salemba and Pinang Ranti demonstrate stronger alignment with sustainable urban living due to better ecological balance. Dukuh Atas represents partial alignment, where TOD-based accessibility improvements still require stronger integration of green infrastructure to fully support climate-resilient urban mobility.

This study has several limitations. First, the analysis is based on three temporal snapshots (2014, 2019, and 2024), which may not fully capture inter-annual variability and short-term climatic fluctuations. Second, the study relies on satellite-derived land surface temperature, which may not fully represent pedestrian-level air temperature conditions. Third, socio-economic and behavioral factors influencing walkability were not directly measured, although they are relevant to urban thermal perception and mobility patterns. These limitations suggest that the results should be interpreted as spatially representative rather than temporally continuous or behaviorally exhaustive.

Future research should integrate higher temporal resolution datasets, such as annual or seasonal time series, to capture more detailed urban thermal dynamics. The inclusion of in-situ temperature measurements and microclimate simulations is also recommended to improve accuracy at pedestrian level. Furthermore, integrating socio-economic indicators and mobility data would strengthen the understanding of how thermal environments influence actual walking behavior. Expanding the analysis to other tropical megacities would also allow broader generalization of typology-based urban heat patterns.

Overall, this study highlights that urban heat in Jakarta is not uniformly distributed but strongly structured by functional typologies. The comparative evidence across Koja, Pasar Minggu, Dukuh Atas, Salemba, and Pinang Ranti demonstrates that urban form, land use, and vegetation structure jointly determine thermal risk and walkability conditions, reinforcing the importance of integrated spatial planning for achieving SDG 11 in rapidly urbanizing tropical cities.

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