Urban heat island distribution, transformation, and projection (Case study: Jakarta City in 2000, 2020, and 2040)

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Abstract. The Urban Heat Island (UHI) phenomenon occurs when urban areas experience higher temperatures than surrounding rural regions due to urbanization, land use changes, and reduced green spaces. In cities like Jakarta, UHI worsens climate change impacts, increases energy consumption, and threatens public health and quality of life. This study analyzes changes in UHI intensity and distribution in Jakarta between 2000 and 2020 and projects its impacts by 2040. The methodology includes analyzing Landsat satellite data to map surface temperature and land use changes, processed using geographic information system (GIS) tools. A 2040 projection is made using an urban climate model simulating temperature trends based on urbanization and land use patterns. Findings suggest that UHI intensity in Jakarta increased significantly from 2000 to 2020, particularly in densely built areas with limited green space. The 2040 projection indicates that without strong mitigation efforts, UHI will continue to rise, negatively affecting public health and increasing energy demand. However, strategies such as expanding green spaces and adopting eco-friendly building technologies can significantly reduce UHI intensity, helping mitigate climate change impacts. This research provides critical guidance for urban planners and policymakers to implement effective UHI mitigation strategies, promoting sustainable urban development and enhancing the resilience of Jakarta's urban environment against future climate challenges.

1 Introduction

Rapid urbanization has become a global phenomenon that significantly influences urban dynamics and development patterns in many parts of the world, including Indonesia. The movement of people from rural areas to urban centers has been one of the defining trends of modern population growth, driven by factors such as economic opportunities, improved access to services, and the perceived quality of life in cities. According to data from the [1], Indonesia has seen a remarkable transformation in its demographic structure over the past few decades. Between 1960 and 2017, the urban population surged by 131.49 million people,

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reflecting the country's transition from a largely rural society to one that is increasingly urban in contrast, rural areas saw only a modest increase of 44.71 million people over the same period, highlighting the concentration of growth in cities. This demographic shift is expected to continue, with predictions from the Central Statistics Agency suggesting that by 2035, around 66.6% of Indonesia's population will reside in urban areas [2].

Rapid urbanization is transforming population distribution and affecting land use, infrastructure, and environmental sustainability. As cities grow, large areas of land are converted into residential, commercial, and industrial zones [3], accompanied by infrastructure development like roads and high-density buildings [4]. This urban expansion increases the demand for materials such as concrete, asphalt, and steel, which absorb heat and contribute to the urban heat island (UHI) effect [5]. The loss of vegetation and green spaces worsens this effect, leading to higher temperatures, increased energy consumption for cooling, pressure on water resources, and poorer air quality, all of which impact public health [6].

Urbanization leads to an increase in UHI intensity, where urban areas experience higher temperatures than surrounding less-developed regions. Research by [7] shows that land cover changes due to urbanization significantly contribute to this UHI intensification, affecting local and global climates. Higher temperatures in urban areas drive increased energy consumption for cooling, particularly in residential and commercial sectors [8]. Jakarta, as a rapidly growing metropolis, exemplifies the impact of urbanization on UHI distribution and intensity, with land cover transformations causing higher surface temperatures than its surroundings [9]. To address these challenges, sustainable and resilient urban planning is crucial, including promoting green infrastructure and climate-resilient strategies [10]. This study aims to analyze UHI distribution, transformation, and projections in Jakarta. The novelty of this research lies in its unique combination of historical (2000–2020) and future (2040) projections of the Urban Heat Island (UHI) effect in Jakarta, using NDVI, NDBI, and LST data. By analyzing how urbanization and land cover changes influence UHI intensity, this study offers new insights into the future dynamics of UHI. It also provides valuable information for urban planners and policymakers to develop sustainable, climate-resilient strategies to mitigate UHI impacts on urban communities

2 Materials and Methods

2.1 Location and Time

Research on the UHI phenomenon was conducted with a case study of Jakarta City. The selection of Jakarta City was made considering the city's rapid urbanization and infrastructure development [3]. Jakarta, one of the world's largest metropolitan cities, is experiencing an increase in temperature due to the increasing number of built-up areas replacing green open spaces. This condition is exacerbated by the absorption of heat by concrete and asphalt surfaces, which causes urban temperatures to be higher than the surrounding areas [11]. Imagery data was obtained in 2000 and 2020 via USGS while 2040 was obtained via projection. The month of image acquisition was selected in August, which coincides with the dry season. This season was chosen because of the low cloud cover and minimal rainfall, allowing the UHI phenomenon to be observed more clearly and its measurement easier [12].

2.2 Materials

The data needed are Landsat 5 for data in 2000 and Landsat 8 for data in 2020 imagery records with 10% cloud cover via USGS. By applying spectral transformations, we converted

Landsat imagery into NDVI, NDBI, LST, and UHI. Table 1 provides information on the classification of each transformation result. The equipment in this study is hardware in the form of a laptop and software in the form of ArcGis Pro 10.8 and a plugin in QGIS namely MOLUSCE (Modules for Land Use Change Evaluation). MOLUSCE is a spatial analysis tool that allows modeling and predicting land use changes based on factors such as topography, distance to roads, and settlements [13]. This plugin will be used to make projections for the next 20 years.

2.3 Data Processing

- Calculation of Top of Atmosphere (TOA):
  TOA = 0.000342 x Band 10 + 0,1……………………………………………...(1)
- Calculation of Brightness Temperature (BT):
  $BT = \frac{K_2}{ln\left(\frac{K^1}{L\lambda}+1\right)} - 273{,}15$……………………………………………….....(2)
- Calculation of the Normalized Difference Vegetation Index (NDVI):
  $NDVI = \frac{(NIR-RED)}{(NIR+RED)}$………………………………………………………..(3)
- Calculation of the Normalized Difference Built-up Index (NDBI):
  $NDBI = \frac{SWIR-NIR}{SWIR+NIR}$……………………………………………………….(4)
- Calculation of the Proportion of Vegetation (PVI):
  $PV = (\frac{NDVI-NDVImin}{NDVImax-NDVImin})^2$……………………………………………(5)
- Calculation of Emissivity (E):
  E = 0,004 x PVI + 0.986…………………………………………………………...(6)
- Calculation of Land Surface Temperature (LST):
  $LST = \frac{BT}{[\,1+\left(\lambda\, x \frac{T}{\partial}\right) x\, ln(e)]}$……………………………………………………(7)
- Calculation of Urban Heat Island (UHI):
  $UHI = \frac{LST-LSTmean}{Standar\ Deviation}$ ………………………………………………………(8)

Table 1. NDVI, NDBI, LST, and UHI classification

NDVI		NDBI		LST		UHI	
Class	**Value**	**Class**	**Value**	**Class**	**Value**	**Class**	**Value**
Non-Vegetation	-1 – 0	Non-Settlement	-1 - 0	1	< 20°C	Non-UHI	≤ 0
Low Vegetation	0.03 – 0.25	Low Settlement	0.1 – 0.3	2	21-24°C	UHI 1	0 - 2
Moderate Vegetation	0.25 – 0.40	Moderate Settlement	0.3 – 0.5	3	25-28°C	UHI 2	2 - 4
High Vegetation	0.40 – 1	High Settlement	≥ 0.5	4	29-32°C	UHI 3	≥ 4
				5	> 32°C		

To perform a projection with the MOLUSCE plugin, the first thing to note is that the data used has the same spatial resolution (cell size) coordinates. Data that can be processed with MOLUSCE is data in raster. The overall data analysis workflow can be seen in Figure 1.

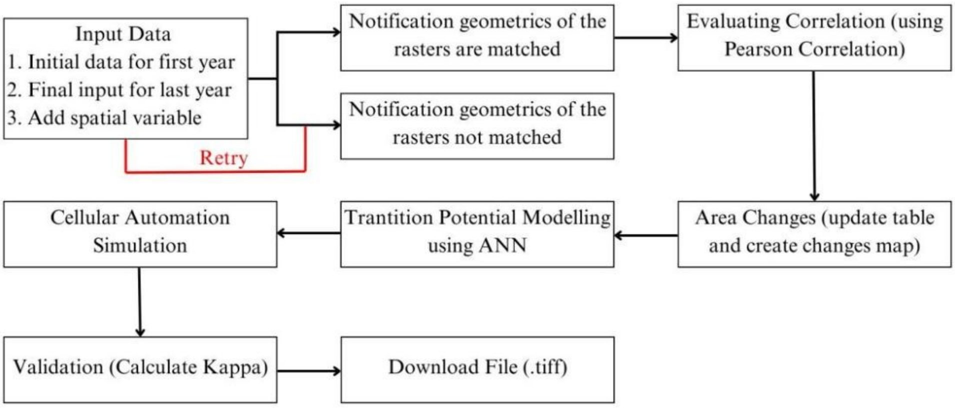


Fig. 1. MOLUSCE analysis

The research uses a descriptive quantitative approach to explain the calculated area and percentage of UHI. A simple correlation analysis is also conducted to examine the relationship between LST and NDVI, as well as LST and NDBI.

3 Result and Discussion

3.1 NDVI Result of Jakarta

NDVI is an important indicator to measure the density and health of vegetation in an area [14]. NDVI values range from -1 to 1, where negative values or close to zero indicate non-vegetated areas (such as water, buildings, or other built-up areas), while values close to 1 indicate areas with high vegetation. In 2000, Jakarta still had significant vegetation cover. Areas with high vegetation (NDVI value 0.40 - 1) reached 906.41 hectares, which is an indicator that there is quite a large green area in the city. Areas with moderate vegetation (NDVI value 0.25 - 0.40) covered 323.60 hectares, and low vegetation (NDVI value 0.03 - 0.25) covered 17.34 hectares. Areas without vegetation or built-up areas only covered 69.67 hectares. Meanwhile, in 2020, there was a drastic change in vegetation cover. The area with high vegetation decreased drastically to 8012.01 hectares, while the area without vegetation increased rapidly to 18757.53 hectares. The increase in the area without vegetation indicates the expansion of built-up areas due to intensive urbanization, which causes the loss of green areas and natural vegetation areas [15]. This decrease in vegetation is caused by land conversion for settlements, infrastructure, and rapid industrialization. The detailed NDVI values can be seen in Table 2, and their spatial distribution is shown in Figure 2.

Table 2. The result of NDVI

City / Year	Class	Value	NDVI (Ha)
Jakarta/2000	Non-Vegetation (1)	-1 – 0	69.670
	Low Vegetation (2)	0.03 – 0.25	17.339
	Moderate Vegetation (3)	0.25 – 0.40	323.599
	High Vegetation (4)	0.40 – 1	906.409
Jakarta/2020	Non-Vegetation (1)	-1 – 0	18757.528
	Low Vegetation (2)	0.03 – 0.25	21670.877
	Moderate Vegetation (3)	0.25 – 0.40	15763.987
	High Vegetation (4)	0.40 – 1	8012.015

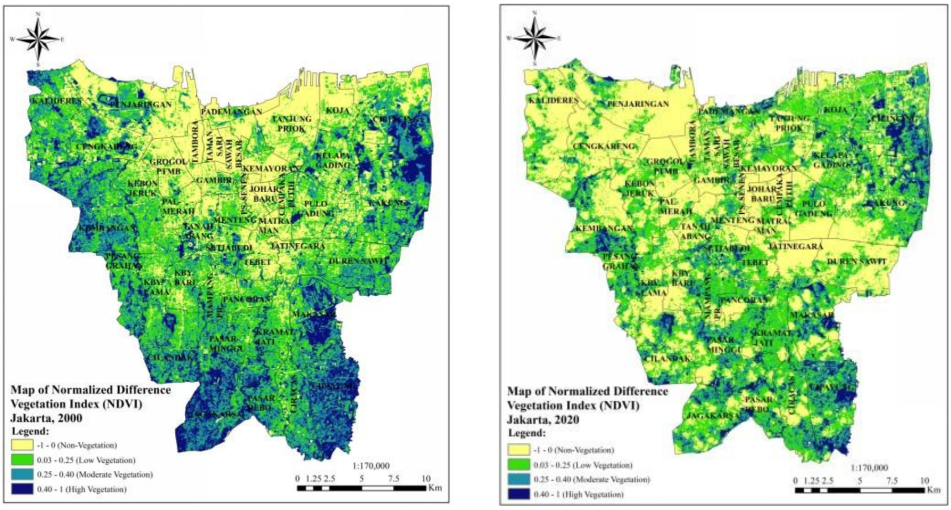


Fig. 2. Normalized Difference Vegetation Index in Jakarta 2000 (left) and 2020 (right)

The drastic decline in vegetation cover from 2000 to 2020 shows that Jakarta faces a major challenge in maintaining the balance between urban growth and environmental sustainability. Without mitigation policies to preserve green areas, the environmental and health impacts of rising temperatures and pollution will become more pronounced.

3.2 NDBI Result of Jakarta

NDBI is used to measure the level of development of built-up areas or areas with man-made structures (such as buildings, roads, and infrastructure) [16]. In 2000, Jakarta's urban landscape was characterized by substantial development, with areas classified as high-density settlements (NDBI value ≥ 0.5) spanning 19,500.53 hectares. This was accompanied by an extensive spread of low to medium-density settlements, covering 16,204.58 hectares and 24,113.94 hectares, respectively. These figures highlight the ongoing urbanization process at the time, as significant portions of the city had already undergone infrastructure expansion and development [17]. By 2020, the city's development trajectory had intensified, with high-density settlement areas expanding sharply to 25,792.89 hectares. This marked a substantial increase in urban infrastructure, particularly in the city’s core, where population growth and economic activities had driven the demand for more residential and commercial space. As a result, non-residential areas decreased significantly, shrinking to 13,414.57 hectares, underscoring the widespread conversion of previously undeveloped or green areas into built-up environments. Detailed information about NDBI in Jakarta can be found in Table 3, and its spatial distribution is shown in Figure 3.

Table 3. The result of NDBI

City / Year	Class	Value	NDBI (Ha)
Jakarta/2000	Non-Settlement (1)	-1	20585.879
	Low Settlement (2)	0.1 – 0.3	16204.578
	Moderate Settlement (3)	0.3 – 0.5	24113.937
	High Settlement (4)	≥ 0.5	19500.528
Jakarta/2020	Non-Settlement (1)	-1	13414.566
	Low Settlement (2)	0.1 – 0.3	15305.979
	Moderate Settlement (3)	0.3 – 0.5	26184.754
	High Settlement (4)	≥ 0.5	25792.894

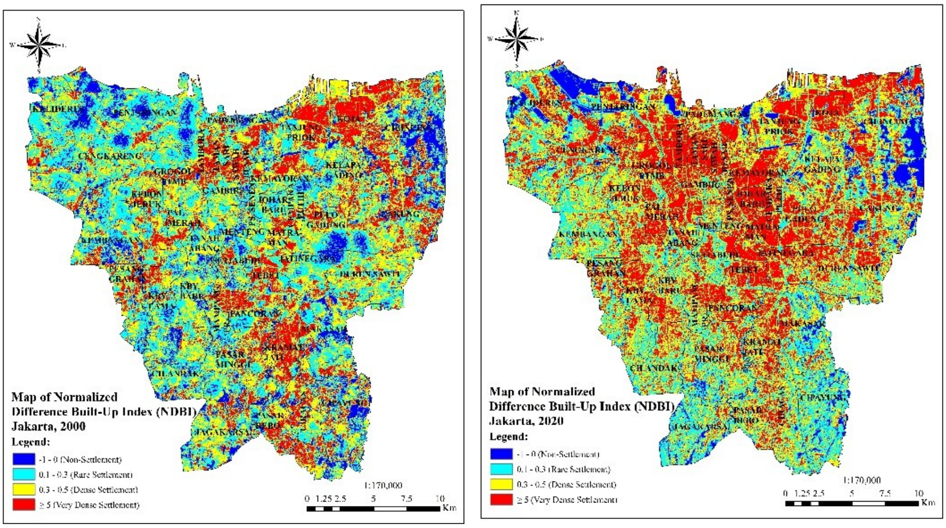


Fig. 3. Normalized Difference Built-Up Index in Jakarta 2000 (left) and 2020 (right)

Jakarta has experienced a large development boom and expansion of built-up areas between 2000 and 2020. This transformation not only reflects Jakarta's rapid urban expansion but also highlights the growing pressure on the city's remaining open spaces, which are essential for mitigating the urban heat island effect, improving air quality, and providing recreational areas for residents. The substantial loss of green and vacant land raises concerns about the long-term sustainability of the city's development [18], as continued urbanization without sufficient planning could further strain its environmental resources, exacerbate heat, and reduce the quality of life for its inhabitants.

3.3 LST Result of Jakarta

Land Surface Temperature (LST) is a key metric used to assess the temperature of the Earth's surface, and it is highly sensitive to shifts in land use and vegetation cover [19] As urban areas expand and vegetation decreases, surface temperatures tend to rise, particularly in densely built-up cities. In Jakarta, this dynamic was evident in 2000, when surface temperatures below 32°C still covered the majority of the city, spanning 40,346.22 hectares. However, there were already signs of increasing heat, with 16,056.70 hectares experiencing temperatures above 32°C. This suggests that, despite ongoing urbanization, cooler zones, likely supported by remaining green spaces continued to dominate the city's landscape at that time. By 2020, the area experiencing temperatures above 32°C expanded to 18,247.52 hectares, reflecting the growing impact of urban development on surface temperatures. The increase in heat is largely attributed to the rise in built-up areas, where natural land cover is replaced with impervious surfaces such as concrete and asphalt. These materials are known for their heat-absorbing properties [20]. Detailed information about LST in Jakarta can be found in Table 4, and its spatial distribution is shown in Figure 4.

Table 4. The result of LST

City / Year	Class	Value	LST (Ha)
Jakarta/2000	1	< 20°C	1099.365969
	2	21-24°C	6304.54699
	3	25-28°C	11860.7548

	4	29-32°C	28882.864
	5	> 32°C	16056.70172
Jakarta/2020	1	< 20°C	9267.109374
	2	21-24°C	6812.947391
	3	25-28°C	9028.926839
	4	29-32°C	20299.18909
	5	> 32°C	18247.51643

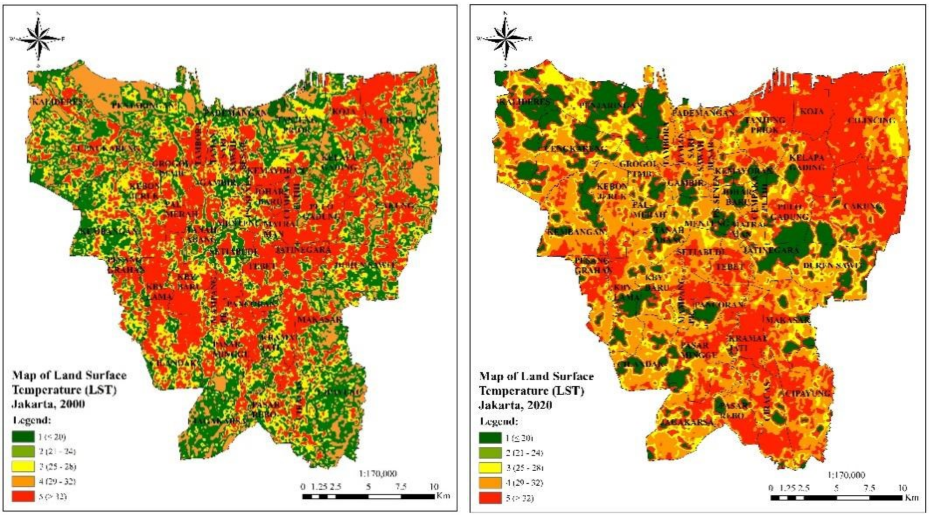


Fig. 4. Land Surface Temperature in Jakarta 2000 (left) and 2020 (right)

This significant rise in surface temperature from 2000 to 2020 underscores the environmental consequences of rapid urban expansion. As built-up areas continue to spread, they not only replace natural land cover but also create conditions conducive to increased heat retention [21]. This has far-reaching implications, particularly in densely populated cities like Jakarta, where rising surface temperatures can affect energy consumption (due to greater demand for cooling), public health (by heightening the risk of heat-related illnesses), and overall urban livability.

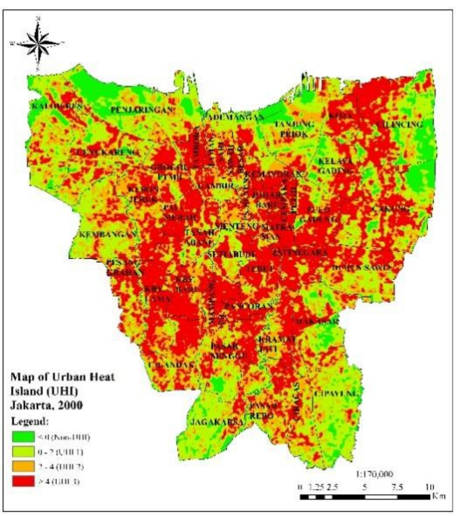
3.4 UHI Result of Jakarta

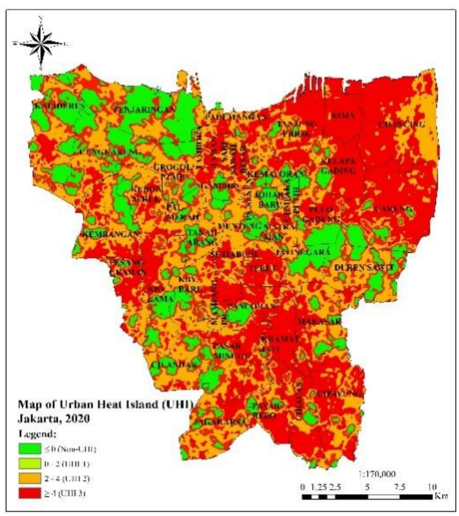
The UHI phenomenon occurs when urban areas experience significantly higher temperatures compared to their rural surroundings, primarily due to the widespread use of heat-absorbing materials like concrete, asphalt, and steel, combined with the loss of natural vegetation [5]. In cities like Jakarta, this effect is becoming more pronounced as urbanization accelerates. In 2000, Jakarta's areas with a high UHI intensity (UHI $\geq$ 4) spanned 16,056.53 hectares. Although urban development was already underway at that time, the UHI effect had not yet become overwhelming, largely because the city still retained a considerable amount of green spaces, which helped moderate temperatures and mitigate the effects of urban heat [22]. However, by 2020, the extent of high UHI areas had expanded sharply, covering 24,067.16 hectares. This increase is a direct consequence of the substantial loss of vegetation and the aggressive expansion of built-up areas throughout the city. As more land is converted into residential, commercial, and industrial zones, green areas that once acted as natural cooling mechanisms have dwindled. Consequently, the UHI effect has intensified, particularly in the city center, where densely packed buildings and impervious surfaces trap and radiate heat.

Looking ahead to 2040, projections paint an alarming picture. It is estimated that the area affected by high UHI intensity will surge to 44,481.31 hectares, nearly encompassing the entire city. This dramatic increase highlights the growing environmental and public health challenges Jakarta will face as urbanization continues unabated. With nearly all areas of the city experiencing elevated temperatures, the impact on the population will be profound, particularly for vulnerable groups such as children, the elderly, and those with pre-existing health conditions. The rise in temperatures will exacerbate health risks, including heat stress, dehydration, and respiratory problems, and place additional pressure on public health systems [23]. Furthermore, the heightened demand for cooling will likely strain energy infrastructure, leading to higher costs and increased greenhouse gas emissions [24], creating a feedback loop that further worsens the city's environmental conditions. Detailed information about UHI in Jakarta can be found in Table 5, and its spatial distribution is shown in Figure 5.

Table 5. The result of UHI

City / Year	Class	Value	UHI (Ha)
Jakarta/2000	Non-UHI	≤ 0	2543.941294
	UHI 1	0 - 2	11466.26567
	UHI 2	2 - 4	34137.30172
	UHI 3	≥ 4	16056.53066
Jakarta/2020	Non-UHI	≤ 0	10973.48016
	UHI 1	0 - 2	8751.045456
	UHI 2	2 - 4	20414.14832
	UHI 3	≥ 4	24067.16284
Jakarta/2040	Non-UHI	≤ 0	9548.417474
	UHI 1	0 - 2	1425.062685
	UHI 2	2 - 4	8751.045456
	UHI 3	≥ 4	44481.31116





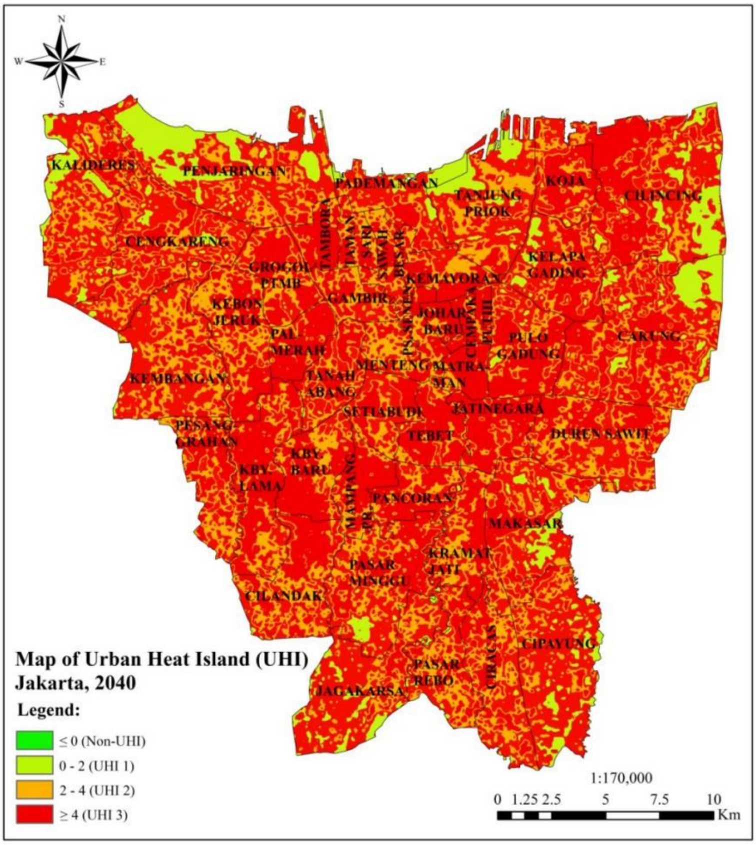


Fig. 5. Urban Heat Island map in Jakarta 2000 (top left), 2020 (top right), and 2040 (bottom)

Projections show that without significant intervention, the UHI phenomenon in Jakarta will increase sharply, creating major challenges for quality of life and the environment. Urbanization without regard for environmental impact mitigation will exacerbate this problem [25]. The increasing dominance of impervious surfaces such as buildings, roads, and industrial zones led to higher heat absorption during the day, which is then re-radiated at night, causing urban areas to maintain higher temperatures compared to surrounding rural areas. This trend is clearly illustrated in the UHI data, which shows that areas affected by UHI, particularly in the high-intensity category, have grown considerably between 2000 and 2020. The projections for 2040 suggest that without intervention, Jakarta's UHI problem will intensify even further, with more extensive areas of the city being exposed to higher temperatures due to ongoing urban expansion and the further decline of green spaces.

To address these challenges, Jakarta must implement sustainable urban planning strategies aimed at mitigating the UHI effect. This includes increasing the city's green spaces, incorporating nature-based solutions such as green roofs and urban forests, and promoting the use of energy-efficient building materials that reflect rather than absorb heat. Without such interventions, the city’s quality of life could decline significantly, with far-reaching implications for its residents' health, well-being, and economic productivity.

4 Conclusion

From the research that has been done, it is known that the distribution of normalized difference vegetation index (NDVI) has been decreasing over the past 20 years, while the distribution of normalized difference built-up Index (NDBI) and land surface temperature (LST) has been increasing from year to year. This shows that NDVI has a negative correlation with LST, where the higher the NDVI, the lower the LST in an area. Meanwhile, if the NDVI is low, the LST will have a high value. On the other hand, NDBI has a positive correlation with LST, where the denser the NDBI in an area, the higher the LST in that area will be. The projections made in 2040 show that the UHI will increase rapidly and cover almost the entire area, reaching 44,481,31116 hectares. The solution that can be done to suppress or inhibit the UHI value so that it does not increase further is to use green roofs, create urban forests, and promote the use of energy-efficient building materials.

References

[1] United Nations 2018 Revision of World Urbanization Prospects. Department of Economic and Social Affairs. Available: https://ourworldindata.org/urbanization. [Accessed: Aug. 30, 2024].

[2] Muzaky H and Jaelani L M 2019 Analysis of the Influence of Land Cover on Surface Temperature Distribution: Urban Heat Island Study in Jakarta, Bandung, and Surabaya. *Jurnal Penginderaan Jauh Indonesia* **2**.

[3] Rustiad E, Pravitasari A E, Setiawan Y, Mulya S P, Pribadi D O, and Tsutsumida N 2021 Impact of Continuous Jakarta Megacity Urban Expansion on the Formation of the Jakarta-Bandung Conurbation Over the Rice Farm Regions. *Cities* **111**.

[4] Shen J and Wu F 2023 Paving the Way to Growth: Transit-Oriented Development as a Financing Instrument for Shanghai's Post-Suburbanization. *Changing Asian Urban Geographies* 28-50.

[5] Nwakaire C M, Onn C C, Yap S P, Yuen C W, and Onodagu P D 2020 Urban Heat Island Studies with Emphasis on Urban Pavements: A Review. *Sustainable Cities and Society* **63**.

[6] N. Nazarian N. Krayenhoff E S, Bechtel B, Hondula D M, Paolini R, Vanos J, and Santamouris M 2022 Integrated Assessment of Urban Overheating Impacts on Human Life. *Earth's Future* **10**.

[7] Khoshnoodmotlagh S, Daneshi A, Gharari S, Vereles J, Mirzaei M, and Omrani H 2021 Urban Morphology Detection and Its Linking with Land Surface Temperature: A Case Study for Tehran Metropolis, Iran. *Sustainable Cities and Society* **74**.

[8] Li X, Zhou Y, Yu S, Gia J, Li H, and Li W 2019 Urban Heat Island Impacts on Building Energy Consumption: A Review of Approaches and Findings. *Energy* **174** 407–419.

[9] Maheng D, Pathirana A, and Zevenbergen 2021 A Preliminary Study on the Impact of Landscape Pattern Changes due to Urbanization: Case Study of Jakarta, Indonesia. *Land* **10**.

[10] Mallick S K, Das P, Maity B, Rudra S, Pramanik M, Pradhan B and Sahana 2021 Understanding Future Urban Growth, Urban Resilience and Sustainable Development of Small Cities using Prediction-Adaptation-Resilience (PAR) Approach. *Sustainable Cities and Society* **74**.

[11] Prasasti I and Sari N M 2017 The Effect of Environmental Condition Changes on Distribution of Urban Heat Island in Jakarta Based on Remote Sensing Data. *International Journal of Remote Sensing and Earth Sciences* **12** 27-40.

[12] Pratiwi A Y and Jaelani L M 2020 Analysis of Urban Heat Island (UHI) Distribution Changes in Surabaya City Using Multitemporal Landsat Satellite Imagery. *Jurnal Teknik ITS* **9**.
[13] Hakim A M Y, Baja S, Rampisela D A, and Arif S 2019 Spatial Dynamic Prediction of Land Use/Land Cover Change (Case Study: Tamalanrea Sub-District, Makassar City). *IOP Conference Series: Earth and Environmental Science* **280**.
[14] Zelený J, Mercado-Bettín D, and Müller F 2021 Towards the Evaluation of Regional Ecosystem Integrity using NDVI, Brightness Temperature and Surface Heterogeneity. *Science of The Total Environment* **796**.
[15] Yang K, Sun W, Luo Y, and Zhao L 2021 Impact of Urban Expansion on Vegetation: The Case of China (2000–2018). *Journal of Environmental Management* **291**.
[16] Suharyadi R, Umarhadi D A, Awanda D, and Widyatmanti W 2022 Exploring Built-Up Indices and Machine Learning Regressions for Multi-Temporal Building Density Monitoring Based on Landsat Series. *Sensors* **22**.
[17] Wei G, He B J, Sun P, Liu Y, Li R, Ouyang X, and Li S 2023 Evolutionary Trends of Urban Expansion and its Sustainable Development: Evidence from 80 Representative Cities in the Belt and Road Initiative Region. *Cities* **138**.
[18] Kim G, Newman G, and Jiang B 2020 Urban Regeneration: Community Engagement Process for Vacant Land in Declining Cities. *Cities* **102**.
[19] Hussain S, Mubeen M, Ahmad A, Majeed H, Qaisrani S A, Hammad H M, and Nasim W 2023 Assessment of Land Use/Land Cover Changes and its Effect on Land Surface Temperature using Remote Sensing Techniques in Southern Punjab, Pakistan. *Environmental Science and Pollution Research* **30** 99202–99218.
[20] Lakatos A and Lucchi E 2024 Thermal Performances of Super Insulation Materials (SIMs): A Comprehensive Analysis of Characteristics, Heat Transfer Mechanisms, Laboratory Tests, and Experimental Comparisons. *International Communications in Heat and Mass Transfer* **152**.
[21] Du J, Xiang X, Zhao B, and Zhou H 2020 Impact of Urban Expansion on Land Surface Temperature in Fuzhou, China using Landsat Imagery. *Sustainable Cities and Society* **61**.
[22] Aboulnaga M, Trombadore A, Mostafa M, and Abouaiana A 2024 Global Cities' Plans to Mitigate Urban Heat Islands Effect Exploiting Urban Green Coverage in Livable Cities: Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening 409-494.
[23] Margolis H G 2021 Heat Waves and Rising Temperatures: Human Health Impacts and the Determinants of Vulnerability. *Climate Change and Global Public Health*, 123-161.
[24] Barreca A, Park R J, Stainier P 2022 High Temperatures and Electricity Disconnections for Low-Income homes in California. *Nature Energy* **7** 1052–1064.
[25] Asabere S B, Acheampong R A, Ashiagbor G, Beckers S C, Keck M, Erasmi S and Sauer D 2020 Urbanization, Land Use Transformation and Spatio-Environmental Impacts: Analyses of Trends and Implications in Major Metropolitan Regions of Ghana. *Land Use Policy* **96**.