

Urban vegetation dynamics and thermal responses to the COVID-19 pandemic mobility restrictions in Yogyakarta

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Abstract

Changes in human activity during the COVID-19 pandemic affected urban environmental conditions, particularly vegetation density and land surface temperature. This study analyzes vegetation and surface temperature changes in Yogyakarta City using Landsat-8 imagery from 2017 to 2022. A remote sensing approach was applied to derive vegetation indices and surface temperature and to compare pre-pandemic and pandemic periods. The results show an increase in minimum vegetation values from 0.027 to 0.048, while mean and maximum values decreased from 0.118 to 0.108 and from 0.309 to 0.276. Vegetation demonstrated a strong negative relationship with built-up areas, with correlation coefficients of -0.780 before the pandemic and -0.721 during the pandemic. Land surface temperature showed an overall cooling trend. These findings confirm that reduced human activity influenced urban thermal dynamics and vegetation patterns, emphasizing their importance for urban environmental resilience. Landsat 8 satellite images from 2017 to 2022 were used in this work to evaluate changes in Yogyakarta City's vegetation, built-up areas, and land surface temperature prior to and during the COVID-19 pandemic. Environmental indicators such as NDVI, NDBI, and LST were calculated using multispectral and thermal data from Landsat 8, obtained via the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provided by the U.S. Geological Survey (USGS, 2025).

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Introduction

The COVID-19 pandemic significantly altered urban environmental conditions worldwide due to mobility restrictions and reduced human activities. Following the declaration of COVID-19 as a global pandemic by the World Health Organization (WHO), many countries, including Indonesia, implemented mobility restrictions that affected transportation, tourism, industrial activity, and urban dynamics ([Indonesia, 2020](#); [Statista, 2020](#)). Beyond health-related impacts, the pandemic also influenced social relationships and emotional connections within communities ([Eddy, 2021](#)). At the same time, several studies suggested that the pandemic accelerated innovation and adaptation processes across multiple sectors, including environmental monitoring and urban management ([Mukherjee, 2021](#)). These changes affected environmental conditions in urban areas, including vegetation dynamics, air quality, and land surface temperature (LST). Remote sensing techniques have become important tools for monitoring urban environmental changes through spatial and temporal observation of land cover and thermal conditions using satellite imagery. This study utilizes Landsat 8 imagery to evaluate environmental changes before and during the COVID-19 pandemic in order to investigate variations in vegetation density and land surface temperature in Yogyakarta City.

Yogyakarta City is one of Indonesia's major tourism and educational centers, with around 20% of its population being students from various regions ([Syakdiah, 2018](#); [Wacano et al., 2021](#)). Renowned for its rich cultural and natural attractions, Yogyakarta has seen rapid growth in its tourism industry in recent years ([Syakdiah, 2018](#)). The rapid growth of tourism and urban infrastructure has increased the expansion of built-up areas and land conversion in recent years ([Duong et al., 2020](#)). During the COVID-19 pandemic, restrictions on tourism, transportation, and community activities significantly reduced urban mobility and anthropogenic activity ([Purwantara dan Ashari, 2025](#); [Purwantara et al., 2021](#)). These conditions make Yogyakarta an important case study for examining how reduced human activity influenced vegetation density and urban thermal conditions.

Remote sensing has become an important tool for monitoring and evaluating urban environmental conditions during the COVID-19 pandemic. Built-up areas can be identified using the Normalized Difference Built-Up Index (NDBI). A previous study reported a positive linear relationship between NDBI and LST, indicating that areas with higher built-up intensity tend to experience higher surface temperatures and denser human activities ([Arif et al., 2024](#)). Among the diverse indicators utilized for environmental assessments, vegetation index and LST transformations play crucial roles in understanding changes in land characteristics through satellite imagery ([Amani et al., 2017](#); [Joiner et al., 2018](#)). The Normalized Difference Vegetation Index (NDVI) is a well-established measure for monitoring vegetation health and density ([Arif et al., 2020](#); [Gao et al., 2013](#); [Han et al., 2019](#)). Urbanization and anthropogenic activities, including land modification and the expansion of urban areas, contribute significantly to increased surface temperatures. Land surface temperature dynamics are influenced by surface energy balance, atmospheric conditions, and the thermal properties of surface materials ([Li et al., 2025](#); [Nwaerema et al., 2019](#); [Weng, 2009](#)).

Recent studies have highlighted the influence of reduced human activities on urban environmental conditions during the COVID-19 pandemic. A previous study found that lockdowns in Milan and Wuhan contributed to variations in NDVI, LST, and other environmental indicators, resulting in temporary ecological improvements and cooling effects in several urban areas. Their findings indicated that reductions in anthropogenic activity influenced vegetation conditions and urban thermal behavior, although the impacts varied depending on land cover dynamics and local environmental characteristics ([Firozjaei et al., 2021](#)).

Urban environments are increasingly vulnerable to rising land surface temperatures and vegetation degradation caused by urban expansion and climate-related pressures. In cities such as Yogyakarta, rapid land-use changes and built-up expansion may intensify the Urban Heat Island (UHI) effect and reduce environmental quality. Vegetation indices and land surface temperature analyses therefore provide important indicators for evaluating urban ecological change. The principal objectives of this research are in two ways: first, to use remotely sensed data to examine changes in NDVI and LST values in Yogyakarta City before and during the COVID-19 pandemic; and second, to provide insight into the precise effects of the pandemic on urban environmental parameters, with a focus on temperature fluctuations and changes in vegetation cover through thorough remote sensing analysis.

Method

This research focuses on Yogyakarta City, situated in the Special Region of Yogyakarta Province, Indonesia spans coordinates from 07°15'24" to 07°49'26" S and 110°24'19" to 110°28'53" E ([Fig1](#)). The city comprises 14 districts and 45 sub-districts and is characterized by predominantly urban land use and relatively flat topography with an elevation of approximately 126 meters above mean sea level ([Wacano et al., 2021](#)). Yogyakarta is located in the southern part of the Merapi fluvio-volcanic plain, so the volcano's activity strongly influences its geological and geomorphological characteristics ([Ashari, 2017](#); [Purwantara et al., 2020](#); [Ashari et al., 2021](#)). Yogyakarta's flat topography influences the city's spatial structure, which in turn affects residents' mobility and the transportation services developed in the city ([Ashari et al., 2024](#); [Ashari et al., 2025](#)). Between 2017 and 2022, land use in Yogyakarta has undergone some modifications; however, these changes have not been substantial.

The 2017–2022 period was selected to provide sufficient baseline conditions prior to the COVID-19 pandemic and to enable a consistent “apple-to-apple” comparison between pre-pandemic conditions (2017–2019) and pandemic conditions (2020–2022). The use of a multi-year baseline reduces the influence of short-term environmental variability and improves the reliability of interannual comparisons. Analysis of the land use data indicates that Yogyakarta City is primarily characterized by built-up areas, primarily residential zones, with agricultural land constituting a smaller fraction of the total area. The overall land use change during this period has remained relatively minimal, suggesting stability in the urban structure despite pressures from urbanization and population growth ([Badan Pusat Statistik Kota Yogyakarta, 2018, 2019, 2020, 2021, 2022, 2023](#)).

Landsat 8 satellite images from 2017 to 2022 were used in this work to evaluate changes in Yogyakarta City's vegetation, built-up areas, and land surface temperature prior to and during the COVID-19 pandemic. Environmental indicators such as NDVI, NDBI, and LST were calculated using multispectral and thermal data from Landsat 8, obtained via the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provided by the U.S. Geological Survey ([USGS, 2025](#)). All available Landsat 8 scenes within each year were utilized to generate annual mean composites for the 2017–2022 period. This approach reduced the influence of seasonal variability, cloud contamination, and short-term atmospheric fluctuations, thereby improving the consistency of interannual comparisons. The acquisition periods and total annual scenes of Landsat 8 imagery used in this study are summarized in [Table 1](#) to ensure temporal consistency, transparency, and comparability in the multi-temporal analysis. The equations used for NDVI, NDBI, and LST calculations are presented in [Table 2](#).

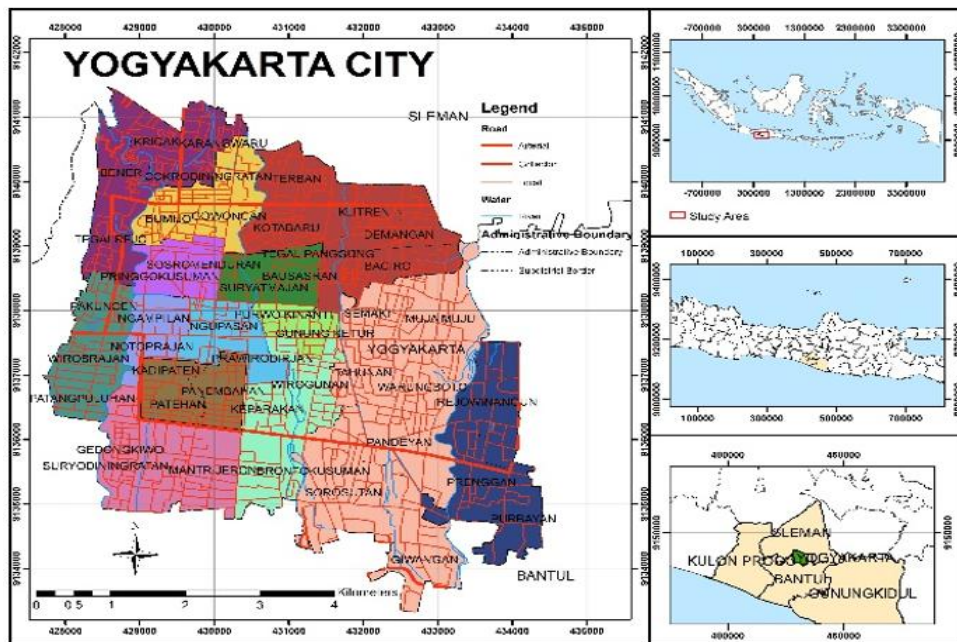


Fig 1. The Yogyakarta City map

Table 1. Landsat 8 image acquisition periods and annual scene availability used in this study

Year	Acquisition Period	Total Scene	Free Cloud Cover
2017	Jan – Dec 2017	23	16
2018	Jan – Dec 2018	23	16
2019	Jan – Dec 2019	22	21
2020	Jan – Dec 2020	22	14
2021	Jan – Dec 2021	23	15
2022	Jan – Dec 2022	23	16

Table 2. Summarizes the equations and methodologies employed

Functions	Algorithm	Source
NDBI	$NDBI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$	(Arif et al., 2024; Zheng et al., 2021)
NDVI	$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$	(Arif et al., 2024; Zheng et al., 2021)
LST	$LST = \left(\frac{BT}{\left(1 + \left(\frac{0.00115 \times BT}{1.4388}\right) \times \ln(Em)\right)} \right)$ $BT = \left(\frac{K2}{\ln\left(\frac{K1}{L\lambda} + 1\right)} \right) - 273.15$ $Pv = \frac{(NDVI - NDVI_{min})}{(NDVI_{max} + NDVI_{min})}$ $Em = 0.0004 \cdot PV + 0.986$	(Arif et al., 2024; Setiawan, 2024)

Assuring data quality, all satellite images were processed using typical computational techniques, such as cloud masking and atmospheric correction. NDVI was used to evaluate vegetation density and its temporal changes because it is widely recognized as an effective indicator for assessing vegetation health and greenness in urban environments, while NDBI was applied to identify and quantify urban built-up areas due to its capability in representing urban expansion and impervious surface intensity associated with urban thermal responses. LST was calculated from thermal infrared bands to examine spatial and temporal variations in surface temperature, which are closely associated with urban expansion and heat stress in densely populated areas (Kikon et al., 2023; Mushore et al., 2022). Previous studies have reported average urban LST values of approximately 28.74 °C in populated regions, highlighting the relevance of LST for urban environmental assessments (Chotchaiwong et al., 2019).

To ensure the reliability of the generated environmental indicators, consistency assessment, cloud masking, atmospheric correction, and comparison with previous urban environmental studies in Yogyakarta City were conducted. In remote sensing-based thermal analysis, LST represents spatial surface thermal characteristics and therefore cannot always be directly compared with ground-based air temperature observations. Remote sensing approaches are particularly useful for evaluating spatial temperature variability across urban environments where ground observations are limited. Previous studies in Yogyakarta City demonstrated that satellite-derived LST showed reasonable agreement with ground-based temperature measurements obtained from the Meteorological, Climatological, and Geophysical Agency, supporting the reliability of Landsat-derived thermal information for environmental analysis (Mahardiani, Insan Wastuwidya; Chiang, 2021).

The combination of NDVI, NDBI, and LST provides a consistent approach for evaluating urban vegetation, built-up areas, and thermal conditions in Yogyakarta City using remote sensing data (Kikon et al., 2023). This analysis relied on average NDVI and LST values calculated for the selected years to observe how vegetation conditions, urban development, and surface temperatures changed before and during the COVID-19 pandemic using remote sensing indicators. This study examined changes across two defined periods, namely the years prior to the COVID-19 pandemic (2017–2019) and the period during the pandemic (2020–2022). The comparison between these periods was conducted to evaluate changes in vegetation conditions, built-up intensity, and surface temperature associated with reduced human activity during the COVID-19 pandemic.

Result and Discussion

Result

This section presents an analysis of urban vegetation dynamics and land surface temperature (LST) in Yogyakarta City across the pre-pandemic and pandemic periods derived from Landsat 8 data. To ensure a consistent and robust "apple-to-apple" comparison, this study utilized all available Landsat 8 scenes for each year (2017–2022) to generate annual mean composites. This multi-temporal approach minimizes the impact of ephemeral atmospheric conditions and seasonal outliers, providing a more stable representation of yearly environmental trends. By integrating vegetation, thermal, and built-up indicators, the analysis reveals how mobility restrictions influenced environmental conditions and highlights the role of urban structure in shaping vegetation dynamics and thermal responses. See [Fig. 2](#)

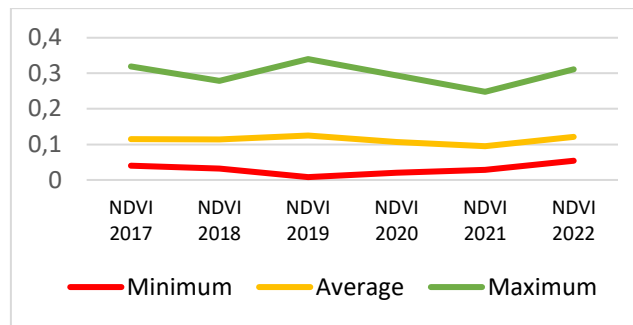


Fig 2. NDVI value in Yogyakarta City from 2017 – 2022

Vegetation Health Trends Variability

The NDVI assessment highlights variations in vegetation conditions across Yogyakarta City during the study period. Based on the annual mean composite analysis, the minimum NDVI increased from 0.027 in the pre-pandemic phase to 0.048 in the pandemic phase, implying partial vegetation recovery in sparsely vegetated zones, potentially due to limitations on human and economic activities. In contrast, the mean NDVI declined from 0.118 to 0.108, and the maximum NDVI decreased from 0.309 to 0.276, indicating an overall reduction in vegetation vitality, even within the city's greener areas. The standard deviation also decreased from 3.324 to 2.863, reflecting a more uniform vegetation condition across the city during the pandemic period. This downward trend in average vitality, consistently captured by the annual composite approach, implies that although human-induced disturbances decreased, the overall urban canopy remained under long-term environmental or developmental pressure.

Spatial patterns of NDVI further support these findings these observations. Prior to the pandemic, higher NDVI values were concentrated in the northern and eastern parts of the city, corresponding to agricultural land and established green spaces, while lower NDVI values dominated the central and western urban core. During the pandemic, areas with relatively higher NDVI expanded slightly into urban districts, suggesting short-term improvements in vegetation health under reduced urban pressure. However, this trend appears temporary, as the easing of restrictions in 2022 likely reintroduced development pressures and tourism-related activities that may have constrained further vegetation recovery. The integration of all available annual scenes confirms that this localized greening was a sustained phenomenon rather than a transient seasonal effect, likely resulting from reduced physical encroachment during the lockdown periods.

Urban Heat Trends and Temperature Variability

The application of annual mean LST composites allows for a high-precision evaluation of the city's thermal baseline, independent of daily meteorological fluctuations. The NDVI assessment provides insights into changes in vegetation condition in Yogyakarta City before and during the COVID-19 pandemic and its linkage with urban thermal behavior. Variations in vegetation density reflect shifts in human activity, which also influenced land surface temperature (LST). Reduced mobility and economic activity during the pandemic affected not only green spaces but also the thermal environment, highlighting the close interaction between vegetation dynamics and urban climate under large-scale social disruptions.

Fig 3 presents the annual LST values from 2017 to 2022. Prior to the pandemic, average LST in 2019 remained relatively stable, reflecting normal urban thermal conditions. During the pandemic, particularly in 2020–2021, LST showed a clear decline, with minimum temperatures reaching approximately 20.5 °C and average LST decreasing to around 25.0 °C. This cooling trend is closely associated with social restriction policies that reduced traffic intensity, industrial activity, and overall anthropogenic heat emissions. This systemic cooling, observed across the yearly

average, provides empirical evidence that the reduction in traffic volume and industrial operations led to a significant decrease in anthropogenic heat flux, thereby moderating the Urban Heat Island (UHI) intensity.

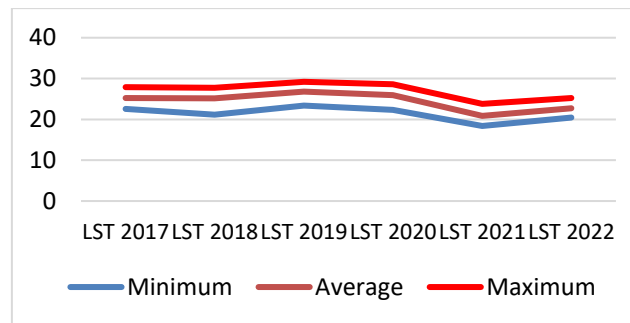


Fig 3. LST value in Yogyakarta City from 2017 – 2022

In 2022, as restrictions were gradually lifted, the average LST increased to approximately 25.5 °C, indicating the return of urban activities and renewed thermal pressure on the city. This rebound suggests that the cooling observed during the lockdown period was temporary and strongly linked to reduced human activity. The pattern emphasizes the need for long-term urban management strategies that can moderate temperature increases alongside economic recovery. The NDBI map (Fig. 4a) shows that built-up areas are predominantly concentrated in the urban core, reflecting the high intensity of residential, commercial, and transportation land uses. Meanwhile, the NDVI maps (Fig. 4b and Fig. 4d) indicate that vegetation cover remained relatively stable before and during the COVID-19 pandemic, with greener areas mainly distributed in the suburban and peri-urban parts of the city. The spatial distribution of LST (Fig 4c and 4e) further illustrates these changes. The minimum LST decreased from 22.435 °C before the pandemic to 20.838 °C during the pandemic, reflecting a substantial reduction in heat generation, particularly in densely built-up areas affected by mobility restrictions.

Average LST across the city declined from 25.717 °C in the before pandemic period to 23.170 °C during the pandemic. Spatially, pre-pandemic conditions (Fig 4c) show higher temperatures concentrated in urban cores, while pandemic conditions (Fig 4e) are dominated by cooler temperatures, especially in central and western areas. The maximum LST also dropped from 27.750 °C to 25.397 °C, and the slight reduction in standard deviation (from 0.690 to 0.638) indicates more uniform temperature conditions across the city during periods of reduced activity. As restrictions eased in 2022, LST values gradually increased, with the average temperature rising to about 25.5 °C. This trend reflects the resumption of transportation, industrial, and economic activities and highlights the direct influence of human activity on urban thermal conditions. The findings underline the importance of mitigating urban heat island effects through sustainable urban planning, particularly in the post-pandemic period.

Urban Heat Trends and Temperature Variability

The results presented in this section focus on the relationships between urban development, vegetation conditions, and surface thermal properties in Yogyakarta City, comparing the periods before and during the COVID-19 pandemic. The use of NDBI, NDVI, and LST as proxies for built-up intensity, vegetation density, and surface thermal conditions enables an assessment of how urban land-use changes corresponded with environmental responses. Comparisons between the pre-pandemic and pandemic periods (2017–2019 and 2020–2022) help to determine whether reduced human activity modified the established relationships between urbanization, vegetation, and

surface heat. [Fig 5](#) illustrates these relationships, highlighting shifts in the strength and direction of correlations among NDBI, NDVI, and LST across the two periods.

To examine the interaction between urbanization, vegetation cover, and surface temperature, this study analyzed the correlations analysis was performed using the synthesized annual data to ensure that the relationship between among NDBI, NDVI, and LST before and during the COVID-19 pandemic represents the long-term urban structure rather than seasonal fluctuations ([Fig 5](#)). The results indicate clear differences between the pre-pandemic period (2017–2019) and the pandemic period (2020–2022). Before the pandemic, the mean NDVI and mean NDBI demonstrated a significant negative association ($r = -0.780$), revealing that lower levels of built-up development were correlated to areas with higher vegetation density. The persistence of this strong inverse relationship in the annual composite data underscores that built-up expansion remains the primary driver of vegetation fragmentation. During the pandemic, this inverse relationship remained evident, with a slightly reduced correlation ($r = -0.721$), suggesting that urban vegetation continued to decline as built-up areas expanded, despite changes in human activity during lockdown periods. These statistical findings confirm that while mobility restrictions lowered the magnitude of heat, the physical urban fabric (built-up area) continues to dictate the spatial distribution of surface temperatures.

LST and NDBI were shown to be positively correlated during both times. Before the COVID-19 pandemic, the correlation between urban density and land surface temperature was high ($r = 0.778$). Although a modest reduction in correlation strength was observed during the pandemic, the relationship remained strong ($r = 0.727$), confirming the persistent contribution of built-up areas to elevated surface temperatures. These findings reinforce the role of urbanization as a key driver of thermal intensification and vegetation loss in Yogyakarta City, even under reduced human activity.

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Discussion

Urban Vegetation Response During Reduced Mobility

a These results highlight the sensitivity of urban vegetation to changes in human activity and land use. Similar findings from Bangladesh show that land cover change, particularly agricultural expansion, exerts a stronger influence on NDVI than climatic factors ([Akhter et al., 2024](#)). This emphasizes how crucial it is to incorporate green space conservation into post-pandemic urban design in Yogyakarta City in order to maintain and improve vegetation resilience in an environment of established urban growth. The observed NDVI dynamics in Yogyakarta City indicate that urban vegetation responses during the COVID-19 pandemic were spatially heterogeneous and strongly influenced by existing land-use characteristics.

Although the increase in minimum NDVI values suggests localized improvements in vegetation greenness, the simultaneous decline in mean and maximum NDVI values indicates that the overall urban vegetation system remained under environmental pressure. This finding suggests that temporary reductions in anthropogenic disturbance during mobility restriction periods were insufficient to fully reverse long-term urban ecological degradation associated with continuous urban expansion and land conversion. In densely urbanized tropical cities such as Yogyakarta, vegetation conditions are not solely controlled by climatic variability but are also strongly affected by the intensity of land development, transportation activity, tourism pressure, and impervious surface expansion.

The relatively modest NDVI improvement observed during the pandemic should therefore not be interpreted as large-scale vegetation recovery or permanent urban greening. Instead, the changes more likely reflect temporary improvements in vegetation condition caused by reduced traffic intensity, lower tourism activity, reduced physical disturbance, and limited human mobility during lockdown periods. Urban vegetation in tropical environments can respond rapidly to short-term reductions in disturbance because vegetation greenness is sensitive to moisture availability, pollution reduction, and lower anthropogenic stress. Similar observations were reported in studies examining environmental responses during the COVID-19 pandemic, where temporary ecological improvements were observed without substantial transformation of urban land-cover structure ([Firozjahi et al., 2021](#); [Mokarram et al., 2024](#)).

The spatial expansion of moderate NDVI values into several urban districts also suggests that small urban green spaces, unmanaged vacant land, roadside vegetation, and residential vegetation may have contributed to localized increases in vegetation greenness during periods of reduced activity. This pattern highlights the ecological importance of fragmented urban greenery in moderating environmental stress within compact urban environments. Even relatively small vegetation patches can contribute to microclimate regulation, surface cooling, and ecological resilience in rapidly urbanizing cities. Consequently, maintaining urban green infrastructure should be considered an essential component of sustainable urban planning strategies in Yogyakarta City, particularly under increasing pressure from tourism development and urban population growth.

Furthermore, the persistence of declining mean NDVI values despite temporary reductions in urban activity indicates that the environmental pressures associated with urbanization remain dominant in shaping vegetation dynamics. This finding suggests that temporary social restrictions alone are insufficient to significantly improve long-term urban ecological quality without structural environmental management strategies. Therefore, urban vegetation conservation should not only focus on preserving existing green spaces but also prioritize the restoration of degraded urban ecosystems and the integration of ecological corridors within densely built urban districts.

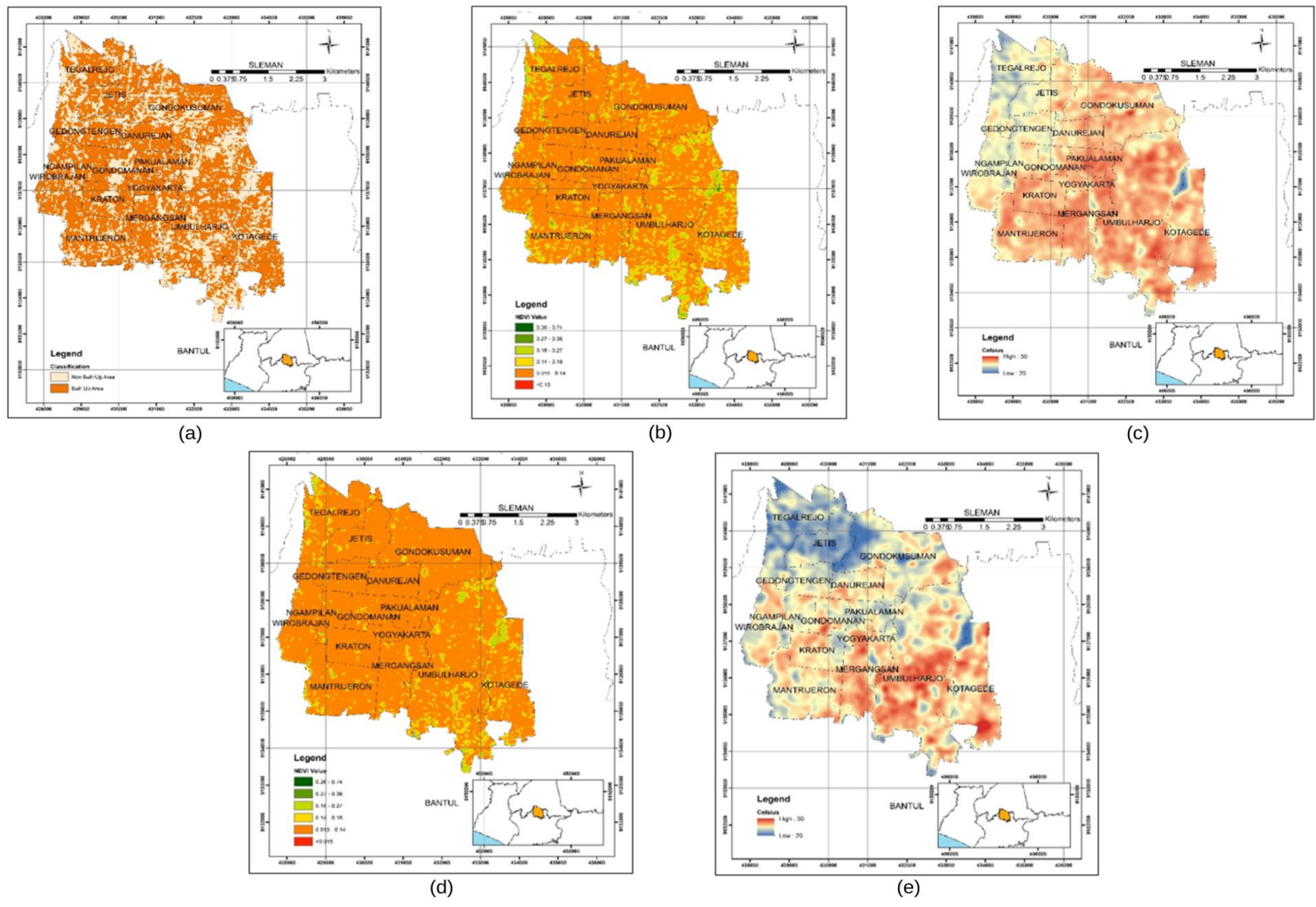


Fig 4. Spatial Distribution of built-up area extracted by NDBI (a), NDVI (b) and LST before the COVID-19 Pandemic (c), NDVI (d) and LST (e) during the COVID 19 pandemic

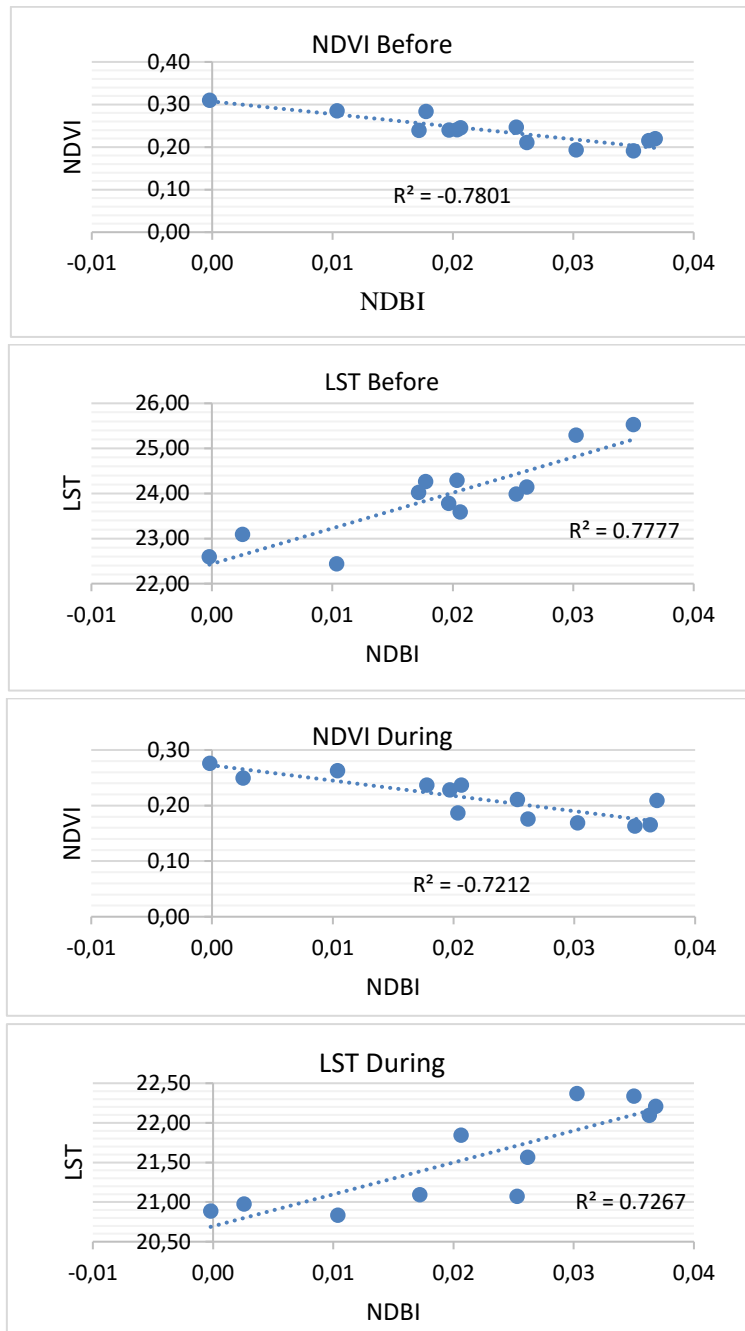


Fig 5. The Correlation between NDBI to NDVI (a) and LST (b) before and NDVI (c) and LST (d) during the COVID-29 Pandemic.

Urbanization and Environmental Pressure

The observed cooling during the pandemic aligns with global evidence of reduced urban heat islands resulting from decreased anthropogenic activity (Parida et al., 2021). Similar relationships between urbanization, land cover change, and increasing LST have been reported in other regions, such as the Lower Son River Basin (Singh et al., 2024). Additionally, previous study Mokarram et al. (2024) demonstrated that reductions in industrial operations and vehicular traffic during the pandemic led to lower air pollution and surface temperatures, reinforcing the consistency of the patterns observed in Yogyakarta City.

The reduction in land surface temperature observed during the pandemic period further demonstrates the strong relationship between anthropogenic activity and urban thermal conditions. In urban environments, thermal accumulation is closely associated with transportation emissions, industrial operations, energy consumption, and the dominance of impervious surfaces that absorb and retain solar radiation. During the COVID-19 pandemic, restrictions on mobility and economic activities significantly reduced these anthropogenic heat sources, leading to measurable cooling effects across many urban regions worldwide. The cooling trend observed in Yogyakarta City therefore reflects not only temporary reductions in traffic and commercial activity but also the sensitivity of urban thermal systems to changes in human behavior and urban intensity.

Nevertheless, the observed cooling should also be interpreted cautiously because the reduction in LST does not necessarily indicate long-term environmental improvement. The increase in average LST values following the gradual relaxation of restrictions in 2022 suggests that the thermal response was temporary and strongly dependent on the level of urban activity. This indicates that without structural changes in land-use planning and environmental management, urban temperatures are likely to continue increasing alongside economic recovery and future urban expansion. Similar post-pandemic thermal rebound patterns have been identified in several rapidly urbanizing cities where surface temperatures increased again following the restoration of transportation and industrial activity ([Mokarram et al., 2024](#); [Parida et al., 2021](#)).

The persistent positive correlation between NDBI and LST also confirms that built-up expansion remains a dominant factor controlling thermal behavior in Yogyakarta City. Areas characterized by dense urban development and high impervious surface coverage tend to experience greater heat accumulation due to lower evapotranspiration capacity and increased solar heat absorption. Conversely, vegetated areas generally contribute to surface cooling through shading effects and evapotranspiration processes. This thermal contrast between built-up and vegetated areas highlights the importance of balancing urban development with ecological preservation to reduce the long-term impacts of urban heat island intensity.

The results highlight the close linkage between land-use change, vegetation dynamics, and urban thermal behavior during the pandemic. Although limited cooling and localized vegetation recovery were observed, the decline in average NDVI suggests that urban green spaces remained under pressure. Similar patterns have been reported in Sleman, Yogyakarta, where a moderate correlation between NDBI and LST indicates increasing heat associated with urban expansion ([Arif et al., 2024](#)). The overall findings indicate that integrating environmental considerations into urban planning is essential for reducing future temperature escalation and maintaining urban vegetation in the post-pandemic context.

The findings also indicate that urban environmental resilience is highly dependent on the balance between built-up intensity and ecological capacity. Rapid urbanization without adequate green infrastructure may accelerate surface heating and environmental degradation, particularly in tropical cities where high solar radiation intensifies thermal accumulation. Consequently, urban climate adaptation strategies should prioritize the expansion of urban vegetation, enhancement of ecological connectivity, and implementation of heat mitigation policies to reduce future thermal vulnerability.

Implications of COVID-19 Mobility Restrictions on Urban Vegetation and Thermal Environment

This research highlights the utility of Landsat 8–derived vegetation indices and land surface temperature as indicators for assessing variations in urban vegetation and thermal responses in Yogyakarta City during periods of reduced mobility associated with the COVID-19 pandemic. The combined use of vegetation, built-up, and thermal indicators enabled a spatially explicit

assessment of how reduced human activity influenced vegetation conditions and surface temperatures, consistent with previous studies highlighting the capability of remote sensing to capture short- to medium-term environmental responses to large-scale social disruptions ([Mokarram et al., 2024](#); [Parida et al., 2021](#)). The observed linkages between urban form, vegetation cover, and thermal behavior further supported findings that built-up expansion strongly controls urban surface temperature patterns ([Shu et al., 2024](#)).

The findings of this study also demonstrate the importance of remote sensing as a practical approach for monitoring urban environmental dynamics during periods of limited field accessibility such as the COVID-19 pandemic. The integration of NDVI, NDBI, and LST derived from Landsat 8 imagery provides a spatially comprehensive representation of urban ecological conditions that would be difficult to achieve using conventional ground-based observations alone. In rapidly changing urban environments, remote sensing enables continuous temporal monitoring and facilitates the identification of environmental responses associated with human activity, land-use modification, and climate-related stressors.

Furthermore, the use of annual mean composites generated from all available Landsat 8 scenes strengthens the reliability of the analysis by minimizing the influence of short-term atmospheric variability and seasonal anomalies. This multi-temporal approach provides a more stable representation of long-term environmental conditions and improves the consistency of interannual comparisons. The methodological framework applied in this study may therefore serve as a useful reference for future urban environmental monitoring studies, particularly in tropical developing cities experiencing rapid urbanization and increasing thermal stress.

The use of all available Landsat 8 scenes strengthens the validity of these findings, as it accounts for the full temporal range of the pandemic's impact. From a sustainability perspective, the results emphasized the importance of integrating green infrastructure into urban development strategies. The robust evidence from annual mean composites suggests that even a temporary reduction in urban intensity can lead to measurable cooling, providing a clear target for future urban heat mitigation. The thermal sensitivity of densely built-up areas and the responsiveness of vegetation during the COVID-19 pandemic of reduced mobility suggested that urban greenery contributes an essential role in moderating surface temperature increases and enhancing urban climate resilience, in line with evidence from both pollution- and temperature-focused remote sensing studies ([Fuladlu, 2024](#); [Mokarram et al., 2024](#)). Policymakers and urban planners can identify priority sites for green space development and protection with the use of remote sensing-based assessments like these, especially in rapid urbanizing cities during post-pandemic recovery phases ([Shu et al., 2024](#)).

From a policy perspective, the observed relationships between vegetation cover, built-up intensity, and thermal conditions indicate that urban climate resilience cannot be separated from land-use planning strategies. The preservation and expansion of urban green spaces may provide multiple environmental benefits, including temperature reduction, ecological stabilization, improved air quality, and enhanced public health conditions. As urban populations continue to increase, the integration of green infrastructure into urban planning policies becomes increasingly important to reduce environmental vulnerability and support sustainable urban development.

Study Limitations and Future Research

Despite these contributions, several limitations should be acknowledged. The analysis relied on a single built-up indicator and medium-resolution satellite imagery (30 m). While annual composites minimize atmospheric noise, the 30m spatial resolution of Landsat 8 may constrain the detection of micro-scale urban greening initiatives. Previous studies have shown that

integrating multiple land use indicators, higher-resolution imagery, and complementary socio-economic or ground-based data can improve the interpretation of urban thermal and environmental processes ([Fuladlu, 2024](#); [Parida et al., 2021](#)). Future research should incorporate multi-sensor fusion (e.g., Sentinel-2 and Landsat) and socio-economic datasets to provide a more granular understanding of long-term urban climate resilience.

In addition, the study primarily focused on remotely sensed environmental indicators and did not directly incorporate detailed socio-economic, demographic, or mobility datasets that may further explain variations in urban thermal and vegetation dynamics during the pandemic. Although reductions in mobility and anthropogenic activity are strongly associated with the observed environmental changes, the complexity of urban ecological systems means that multiple interacting factors may also influence NDVI and LST variability. Climatic fluctuations, precipitation variability, seasonal vegetation cycles, and local urban morphology may contribute to changes in environmental conditions alongside pandemic-related restrictions.

Another limitation relates to the interpretation of vegetation dynamics within highly urbanized environments. NDVI-based assessments primarily capture vegetation greenness rather than ecological quality or biodiversity conditions. Consequently, increases in NDVI values during the pandemic do not necessarily indicate substantial ecological restoration or long-term environmental recovery. Instead, the observed changes may reflect temporary shifts in vegetation condition, unmanaged vegetation growth, or reduced anthropogenic disturbance during periods of restricted mobility. Therefore, caution is required when interpreting short-term NDVI changes as indicators of permanent urban ecological improvement.

Furthermore, the thermal analysis in this study utilized land surface temperature derived from satellite observations rather than direct near-surface air temperature measurements. Although satellite-derived LST provides spatially comprehensive thermal information, differences between surface temperature and atmospheric temperature should be considered when interpreting urban thermal conditions. Nevertheless, previous studies demonstrated that Landsat-derived LST in Yogyakarta City showed reasonable agreement with ground-based observations, supporting its applicability for urban environmental assessment ([Mahardiani et al., 2021](#)).

Future research should incorporate multi-sensor fusion approaches, such as the integration of Sentinel-2 and Landsat imagery, to improve spatial resolution and temporal consistency in urban environmental monitoring. The inclusion of socio-economic indicators, transportation intensity data, air quality measurements, and mobility datasets would also provide a more comprehensive understanding of the interactions between urban activity, vegetation dynamics, and thermal behavior. In addition, future studies may benefit from applying machine learning approaches and urban climate modeling techniques to better predict long-term urban environmental responses under different development and climate scenarios.

Longer temporal observations extending beyond the pandemic period are also necessary to determine whether the environmental changes observed during COVID-19 represent temporary anomalies or indicate longer-term urban ecological trends. Such longitudinal analyses would improve understanding of how rapid urbanization, climate variability, and human activity collectively influence urban environmental resilience in tropical cities such as Yogyakarta City.

Conclusion

According to the research aims, this study examined how the COVID-19 pandemic affected Yogyakarta City's urban vegetation and thermal circumstances. During the pandemic period, the minimum vegetation index increased from 0.027 to 0.048, while the average and maximum values declined from 0.118 to 0.108 and from 0.309 to 0.276, respectively, indicating that reduced human activity did not translate into an overall improvement in vegetation condition. The analysis revealed

a temporary cooling in land surface temperature, reflected by decreases in minimum, mean, and maximum temperatures from 22.435 °C to 20.838 °C, 25.717 °C to 23.170 °C, and 27.750 °C to 25.397 °C. While the positive correlation between built-up areas and surface temperature persevered, declining from 0.784 to 0.716, the negative correlation between vegetation and built-up intensity remained significant, with correlation values of -0.773 before and -0.758 during the pandemic. The strong correlation between urban activities and temperatures was further proved by the average surface temperature rising to almost 25.5 °C once mobility limitations were loosened in 2022. These findings indicated that short-term mobility restrictions alone were insufficient to enhance urban environmental quality, emphasizing the need for long-term urban planning strategies to reduce thermal stress and vegetation loss.

Recommendations

The study demonstrates that the inclusion of remote sensing indicators, namely NDVI, LST, and NDBI, can enhance urban environmental assessments and support more informed urban planning strategies. The temporary cooling observed during periods of reduced human activity underscores the sensitivity of urban thermal conditions to mobility and land-use intensity, while the post-pandemic rebound emphasizes the urgency of climate-responsive urban strategies. Strengthening green infrastructure and managing urban expansion are essential for enhancing ecological resilience, mitigating urban heat, and supporting sustainable urban development in Yogyakarta City, particularly in anticipation of future societal or environmental disruptions.

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Author Contribution

The author conceived and designed the study, collected and analyzed the data, interpreted the results, and wrote the manuscript. The author read and approved the final manuscript.

Data Availability Statement

All data generated or analyzed during this study are presented in the tables and figures within this article.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

Akhter et al. (2024). Akhter, J., & Afroz, R. (2024). *Influence of climate variability and land cover dynamics on the spatio-temporal NDVI patterns in western hydrological regions of Bangladesh*. *Heliyon*, 10, e32625. <https://doi.org/10.1016/j.heliyon.2024.103262>.

- Amani, M., Salehi, B., Mahdavi, S., Masjedi, A., & Dehnavi, S. (2017). Remote Sensing of Environment Temperature-Vegetation-soil Moisture Dryness Index (TVMDI). In *Remote Sensing of Environment* (Vol. 197, pp. 1–14). <http://dx.doi.org/10.1016/j.rse.2017.05.026>
- Arif et al. (2024). Arif, N., & Toersilowati, L. (2024). *Monitoring and predicting development of built-up area in suburban areas A case study of Sleman, Yogyakarta, Indonesia. Heliyon, 10, e34466. <https://doi.org/10.1016/j.heliyon.2024..pdf>.*
- Arif, N., Danoedoro, P., Hartono, & Mulabbi, A. (2020). Erosion prediction model using fractional vegetation cover. In *Indonesian Journal of Science and Technology* (Vol. 5, Issue 1, pp. 125–132). <https://doi.org/10.17509/ijost.v5i1.21060>
- Ashari, A. (2017). Geomorphology of the southern flank of Merapi volcano in relation to the potential hazards and natural resources: a review. *Geomedia Majalah Ilmiah dan Informasi Kegeografian*, 15(2).
- Ashari, A., Purwantara, S., Arif, N., & Widodo, E. (2021). Spatial evolution of the river valleys under the influence of active volcano: A case of Merapi volcanic plain. *Quaestiones Geographicae*, 40(3), 45-64.
- Ashari, A., Olivia, R. A., Reswari, A. Z. A., Brotowiranti, R. W., Hadi, B. S., & Ervin, M. (2024). Reciprocal-relationship between the development of " Trans Jogja " public transportation and urban spatial structure in Yogyakarta agglomeration. *Geomedia Majalah Ilmiah dan Informasi Kegeografian*, 22(1).
- Ashari, A., Nurussolikhin, R. P. S., Putri, A., Ervin, M., & Wardoyo, M. A. I. (2025). Spatio-temporal patterns of air quality on commuter lane of the sub-urban area of Yogyakarta, Indonesia. *Environmental Research and Technology*, 8(2), 354-371.
- Badan Pusat Statistik Kota Yogyakarta. (2018). *No Title*. Kota Yogyakarta Dalam Angka 2018. <https://jogjakota.bps.go.id/id/publication/2018/08/16/8e60dd366fc77ddee9ea008/kota-yogyakarta-dalam-angka-2018.html>
- Badan Pusat Statistik Kota Yogyakarta. (2019). *No Title*. Yogyakarta Dalam Angka 2019. <https://jogjakota.bps.go.id/id/publication/2019/08/16/d551adc84034fd8d954aa642/kota-yogyakarta-dalam-angka-2019.html>
- Badan Pusat Statistik Kota Yogyakarta. (2020). *No Title*. Kota Yogyakarta Dalam Angka 2020. <https://jogjakota.bps.go.id/id/publication/2020/04/27/2a6bb713d16b766c86776231/kota-yogyakarta-dalam-angka-2020.html>
- Badan Pusat Statistik Kota Yogyakarta. (2021). *No Title*. Kota Yogyakarta Dalam Angka 2021. <https://jogjakota.bps.go.id/id/publication/2021/02/26/4c85e0454525ceebd064473a/kota-yogyakarta-dalam-angka-2021.html>
- Badan Pusat Statistik Kota Yogyakarta. (2022). *No Title*. Kota Yogyakarta Dalam Angka 2022. <https://jogjakota.bps.go.id/id/publication/2022/02/25/8771c64c1a932bd8dc54877c/kota-yogyakarta-dalam-angka-2022.html>
- Badan Pusat Statistik Kota Yogyakarta. (2023). *No Title*. Kota Yogyakarta Dalam Angka 2023. <https://jogjakota.bps.go.id/id/publication/2023/02/28/9510c8b16be475ce64f99471/kota-yogyakarta-dalam-angka-2023.html>
- Chotchaiwong et al. (2019). Chotchaiwong, P., & Wijitkosum, S. (2019). *Relationship between land surface temperature and land use in Nakhon Ratchasima City, Thailand. Engineering Journal, 23(4), 1–14. <https://doi.org/10.4186/ej.2019.23.4.1.pdf>.*
- Duong, M. T. T., Samsura, D. A. A., & van der Krabben, E. (2020). Land conversion for tourism development under vietnam's ambiguous property rights over land. *Land*, 9(6), 1–22. <https://doi.org/10.3390/land9060204>

- Eddy, C. M. (2021). The social impact of COVID-19 as perceived by the employees of a UK mental health service. *International Journal of Mental Health Nursing*, 30(S1), 1366–1375. <https://doi.org/10.1111/inm.12883>
- Firozjaei, M. K., Fathololomi, S., Kiavarz, M., Arsanjani, J. J., Homaei, M., & Alavipanah, S. K. (2021). Modeling the impact of the COVID-19 lockdowns on urban surface ecological status: A case study of Milan and Wuhan cities. *Journal of Environmental Management*, 286(February), 112236. <https://doi.org/10.1016/j.jenvman.2021.112236>
- Fuladlu, K. (2024). Human activities and increased anthropogenic emissions: A remote sensing study in Cyprus. *Environmental Development*, 51(June), 101023. <https://doi.org/10.1016/j.envdev.2024.101023>
- Gao et al. (2013). Gao, Z., Xu, X., Wang, J., Yang, H., Huang, W., & Feng, H. (2013). Estimating soil moisture based on linear decomposition of mixture pixels. *Mathematical and Computer Modelling*, 58(3–4), 606–613. <https://doi.org/10.1016/j.mcm.2013.03.013>
- Han et al. (2019). Han, J. C., Huang, Y., Zhang, H., & Wu, X. (2019). NDVI variations related to elevation and land cover in northwest China. *Journal of Environmental Management*, 232, 1037–1048. <https://doi.org/10.1016/j.jenvman.2018.11.011>
- Indonesia, M. of H. (2020). *No Title*. Peraturan Menteri Kesehatan Republik Indonesia Nomor 9 Tahun 2020 Tentang Pedoman Pembatasan Sosial Berskala Besar Dalam Rangka Percepatan Penanganan Corona Virus Disease 2019 (COVID-19). <https://farmalkes.kemkes.go.id/unduh/permenkes-9-2020/>
- Joiner, J., Yoshida, Y., Anderson, M., Holmes, T., Hain, C., Reichle, R., Koster, R., Middleton, E., & Zeng, F. W. (2018). Global relationships among traditional reflectance vegetation indices (NDVI and NDII), evapotranspiration (ET), and soil moisture variability on weekly timescales. *Remote Sensing of Environment*, 219(October), 339–352. <https://doi.org/10.1016/j.rse.2018.10.020>
- Kikon et al. (2023). Kikon, N., Kumar, D., & Ahmed, S. A. (2023). LST and vegetation indices at kilometer scale. *Environmental Science and Pollution Research*, 30(49), 107236–107258. <https://doi.org/10.1007/s11356-023-27418-y>
- Li et al. (2025). Yuan Li, Yingfeng Wang, Mengsheng Yang, Yanan Du, Jingge Liu, What is the relationship between urban heat island (UHI) effect and urban surface parameter (USP) at micro-scale A case study in Gulangyu, China, *Sust*.pdf.
- Mahardiani, Insan Wastuwidya; Chiang, S. H. (2021). *Impact of Temperature on Tuberculosis estimated from Satellite Remote Sensing before and during COVID-19 Pandemic*. 22–24.
- Mokarram, M., Taripanah, F., & Minh Pham, T. (2024). Assessing air pollution changes during the COVID-19 and its impact on the urban environment using remote sensing and neural networks. *Advances in Space Research*, 73(3), 1760–1779. <https://doi.org/10.1016/j.asr.2023.11.039>
- Mukherjee, K. (2021). Integrating technology, innovation and policy: COVID-19 and HTA. *Health Policy and Technology*, 10(1), 16–20. <https://doi.org/10.1016/j.hlpt.2021.01.003>
- Mushore et al. (2022). Mushore, T. D., Mutanga, O., & Odindi, J. (2022). Estimating urban LST using multiple remotely sensed spectral indices and elevation retrievals. *Sustainable Cities and Society*, 78, 103623. <https://doi.org/10.1016/j.scs.2022.103623>
- Nwaerema, P., Vincent, O. N., Amadou, C., & Morrison, A. I. (2019). Spatial Assessment of Land Surface Temperature and Emissivity in the Tropical Littoral City of Port Harcourt, Nigeria. In *International Journal of Environment and Climate Change* (pp. 88–103). <https://doi.org/10.9734/ijecc/2019/v9i230099>

- Parida et al. (2021). Parida, B. R., et al. (2021). Impact of COVID-19 induced lockdown on land surface temperature, aerosol, and urban heat in Europe and North America. *Sustainable Cities and Society*, 75, 103336. <https://doi.org/10.1016/j.pdf>.
- Purwantara, S., Ashari, A., & Ibrahim, M. H. B. (2020). The characteristics of infiltration on the southern flank of Merapi volcanic plain, Yogyakarta, Indonesia. *GEOMATE Journal*, 19(74), 201-209.
- Purwantara, S., Ashari, A., & Putro, S. T. J. (2021). The relationship between landscape and meteorological parameters on COVID-19 risk in a small-complex region of Yogyakarta, Indonesia. *Bulletin of Geography. Physical Geography Series*, (21), 27-43.
- Purwantara, S., & Ashari, A. (2025). Spatio-temporal variability of urban surface temperature during COVID-19 pandemic: A study from some selected cities in Indonesia and Singapore. *Jurnal Wilayah Dan Lingkungan*, 12(3), 279-292.
- Setiawan. (2024). Setiawan, N. (2024). Integration of Landsat-8 OLI/TIRS and Sentinel-1A PolSAR for analyzing land surface temperature and its anomalies linked to ENSO in Surakarta, Indonesia. *Geomatica*, 76, 100038. <https://doi.org/10.1016/j.pdf>.
- Shu et al. (2024). Shu, B., Chen, Y., Amani-Beni, M., & Dehghanifarsani, L. (2024). Urban engineering insights Spatiotemporal analysis of land surface temperature and land use in urban landscape. *Alexandria Engineering Journal*, 92, .pdf.
- Singh, S., Kumar, P., Parijat, R., Gonengcil, B., & Rai, A. (2024). Establishing the relationship between land use land cover, normalized difference vegetation index and land surface temperature: A case of Lower Son River Basin, India. In *Geography and Sustainability* (Vol. 5, Issue 2, pp. 265–275). <https://doi.org/10.1016/j.geosus.2023.11.006>
- Statista. (2020). *No Title*. Number of Total COVID-19 Cases in Indonesia as of March 9, 2023. <https://www.statista.com/statistics/1103469/indonesia-covid-19-total-cases/?srsltid=AfmBOorN8MxCIdCma0dtByK1uriBzQxbZ5ioJmcJ0xguh2qODx9dAqIW>
- Syakdiah, S. (2018). Dynamics of Tourism in Special District of Yogyakarta. *Prosiding Semnasfi*, 7(1), 225. <https://doi.org/10.21070/semnasfi.v1i1.1135>
- USGS. (2025). *No Title*. Landsat-8. <https://www.usgs.gov/landsat-missions/landsat-8>
- Wacano, D., Latifah, N. D., Bishop, H., Gutama, H., Hasanah, N. A. I., Yulianto, A., Rahmawati, S., Nurmiyanto, A., Putra, H. P., Maziya, F. B., Ardhayanti, L. I., Lathifah, A. N., & Asmara, A. A. (2021). Landscapes Vulnerability on Climate Change in Yogyakarta Province, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 933(1). <https://doi.org/10.1088/1755-1315/933/1/012027>
- Weng, Q. (2009). Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. In *ISPRS Journal of Photogrammetry and Remote Sensing* (Vol. 64, Issue 4, pp. 335–344). <https://doi.org/10.1016/j.isprsjprs.2009.03.007>
- Zheng et al. (2021). Zheng, Y., Tang, L., & Wang, H. (2021). An improved approach for monitoring urban built-up areas by combining NPP-VIIRS nighttime light, NDVI, NDWI, and NDBI. *Journal of Cleaner Production*, 328, 129488. <https://doi.org/10.1016/j.pdf>.