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# Analysis of the Linking Vegetation, Buildings, and Carbon Footprint to Urban Heat Island Effects in Surakarta

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**ABSTRACT**

The city of Surakarta, serving as a center for governance, community welfare, and economic activities, is experiencing increased population density, land-use changes, and rising carbon emissions, resulting in significant temperature differences compared to its surrounding areas—a phenomenon known as the Urban Heat Island (UHI). This study aims to map the distribution of carbon emissions, vegetation density, and building density in Surakarta; analyze the relationship between these factors and UHI; and determine the distribution of UHI within the city. Sampling was conducted using Stratified Random Sampling on Landsat 8 imagery. Data analysis employed correlation and multiple linear regression. The results indicate that household electricity emissions in Surakarta contribute 8,708 tons of $CO_2$ across its five districts. Jebres District has the highest vegetation cover (125.87 ha), while Serengan District has the highest building density and non-vegetated areas (55.48 ha). A moderate correlation was observed between NDBI and UHI (0.453) as well as NDVI and UHI (-0.434), indicating that higher NDBI values are associated with increased UHI, while lower NDVI values are linked to higher UHI. Serengan experiences the highest levels of UHI, whereas Banjarsari has the lowest UHI levels.

***Keyword***: *Urban Heat Island, vegetation density,* *carbon emission footprint, building density, NDVI, NDBI, Surakarta*

**ABSTRAK**

Kota Surakarta, yang berfungsi sebagai pusat pemerintahan, kesejahteraan masyarakat, dan kegiatan ekonomi, mengalami peningkatan kepadatan penduduk, perubahan penggunaan lahan, dan kenaikan emisi karbon, yang menyebabkan perbedaan suhu signifikan dengan daerah sekitarnya—dikenal sebagai fenomena Urban Heat Island (UHI). Penelitian ini bertujuan memetakan distribusi emisi karbon, kerapatan vegetasi, dan kepadatan bangunan di Surakarta; menganalisis hubungan ketiganya dengan UHI; dan menentukan distribusi UHI di dalam kota. Pengambilan sampel menggunakan Stratified Random Sampling citra Landsat 8. Analisis data dilakukan dengan korelasi dan regresi linear berganda. Hasil penelitian menunjukkan bahwa emisi listrik rumah tangga di Surakarta menyumbang 8.708ton $CO_2$ di lima kecamatan. Kecamatan Jebres memiliki tutupan vegetasi tertinggi (125,87 ha), sedangkan Kecamatan Serengan memiliki kepadatan bangunan dan area non-vegetasi tertinggi (55,48 ha). Korelasi sedang diamati antara NDBI dan UHI (0,453) serta NDVI dan UHI (-0,434), yang menunjukkan bahwa nilai NDBI yang lebih tinggi berkorelasi dengan peningkatan UHI, sedangkan nilai NDVI yang lebih rendah berkorelasi dengan peningkatan UHI. Serengan mengalami tingkat UHI tertinggi, sedangkan Banjarsari memiliki tingkat UHI terendah.

**Kata Kunci**: Urban Heat Island, kerapatan vegetasi, jejak emisi karbon, kepadatan bangunan, NDVI, NDBI, Surakarta

## INTRODUCTION

Surakarta City serves as a center for government, economic activities, tourism, and quality of life improvements, leading to rapid development across various sectors. Urban areas have become increasingly dense, with people migrating from suburban areas. Many rural residents move to the city seeking better opportunities to improve their quality of life. With centralized development in Indonesia, urbanization is steadily increasing in major cities each year (Adlina, 2019; Hidayat & Nurfauzan, 2022; Hidayati, 2021; Nabal & Djaja, 2022; Praatiwi et al., 2024). Data shows that in 2016, inbound migration reached 8,734 people, surpassing outbound migration of 7,789 people (Wibisono et al., 2023). This trend drives increased demand for housing and infrastructure, leading to the conversion of green spaces into built-up areas such as residential, commercial, and industrial zones. As the population grows, so do the basic needs, especially housing, which drives land conversion into built-up areas, limiting evaporation. Previously agricultural or pastoral lands are converted into residential or industrial uses (Bai et al., 2012; Enoguanbhor et al., 2019). The reduction in green spaces due to urban expansion contributes to the Urban Heat Island (UHI) effect.

The Urban Heat Island (UHI) effect, a phenomenon of temperature rise in urban areas driven by population growth and increased human activities, has become a critical issue in many developing cities, including in Indonesia. UHI is characterized by concentrated hot air zones in city centers, with lower temperatures in suburban areas. Urbanization exacerbates this phenomenon through the conversion of green spaces into built-up areas, reducing vegetation that serves as a natural heat absorber. Humanity's exploitation of nature has been the main contributor to global warming, with greenhouse gases produced from human activities accumulating in Earth's atmosphere over time, thereby increasing surface temperatures. Carbon dioxide concentration is currently the dominant factor in the atmosphere (Ketaren, 2023; Mannan et al., 2024) Carbon dioxide concentrations increase annually, which then raises temperatures. In 2001, Earth's temperature rose by 0.6°C, the highest increase in a century (Arisandi, 2011, in Ngurah et al., 2016). Therefore, assessing human activities that produce carbon dioxide has become crucial. High urban air temperatures create a unique microclimate (Mulyani, 2021; Panjaitan et al., 2023; Setyo et al., 2024) UHI intensity refers to the temperature difference between a city and its surrounding areas. According to Oke (1997, in Wulandari & Sudibyakto, 2017), UHI is an example of unintentional climate change caused by human activities. Several factors contribute to UHI, including weather, location, urban characteristics, and carbon emission footprint. Surakarta faces tangible challenges from the UHI effect, with a growing temperature disparity between the city center and its outskirts. Studies indicate that the maximum temperature in Surakarta reaches 32.7°C, with a UHI intensity of 11.4°C (Wulandari & Sudibyakto, 2017). Other research records a surface temperature difference of ±1-2.5°C between the city center and surrounding areas. Highlighting urbanization's critical role in intensifying UHI. The conversion of green spaces into built-up areas, particularly in Jebres District, which recorded the highest UHI intensity of 4.3°C in 2019. is a significant contributing factor. Consequently, the unique microclimate formed in Surakarta not only deteriorates environmental quality but also affects urban residents' thermal comfort, making UHI a severe impact of urbanization that requires urgent attention.

The carbon emission footprint refers to greenhouse gas emissions produced by an organization, event, product, or person. The amount of carbon ($CO_2$) humans produce stems from everyday activities like lighting, using electronics, eating, and traveling. The carbon footprint measures the total

$CO_2$ emissions directly linked to the frequency of activities and overuse of products, such as burning fossil fuels in motor vehicle use (Wiedemann and Minx, 2007, in Nurhayati, 2015). There are two types of carbon emission footprints: primary and secondary. The primary carbon footprint measures direct emissions from fossil fuel-based products like vehicles, while the secondary footprint measures indirect emissions generated externally from products we use, such as electricity (Walser, 2010, in Nurhayati, 2015). The carbon emission footprint in Surakarta reflects urban activities that significantly contribute to greenhouse gas emissions. Primary carbon emissions mainly come from the transportation sector, with motorcycles nationwide reaching 125,305,332 units in 2022, with Surakarta contributing a significant share. (Agustin & Suhartini, 2023; Prastiyo et al., 2020).

Surakarta is located in Central Java Province, with an area of 4,404.06 ha divided into five districts: Laweyan, Serengan, Pasar Kliwon, Jebres, and Banjarsari. According to the Surakarta City Statistics Agency (BPS, 2020), 65% of land use was for residential purposes in 2014. The city's population has been steadily increasing, with economic activities occupying around 16% of the available land. Surakarta's population is projected to continue growing, as presented in Table 1.1.

**Table 1.** Population of Surakarta City

| No. | Kecamatan | Jumlah Penduduk (Jiwa) | | | | |
|---|---|---|---|---|---|---|
| | | 2016 | 2017 | 2018 | 2019 | 2020 |
| 1 | Laweyan | 43.042 | 43.247 | 43.453 | 43.659 | 43.867 |
| 2 | Serengan | 21.721 | 21.824 | 21.928 | 22.033 | 22.137 |
| 3 | Pasar Kliwon | 37.772 | 37.952 | 38.132 | 38.314 | 38.496 |
| 4 | Jebres | 68.762 | 69.089 | 69.418 | 69.748 | 70.080 |
| 5 | Banjarsari | 79.002 | 79.378 | 79.414 | 80.136 | 80.517 |
| | Jumlah | 250.299 | 251.490 | 252.345 | 253.890 | 255.097 |

*Source: BPS Surakarta City in 2021*

Surakarta City is an urban area serving as a center for government, community welfare, and economic activities. Given these roles, Surakarta has fulfilled its social welfare function, particularly through educational activities. These educational activities generate mobility based on student movements using educational facilities. The population density in Surakarta City reaches 11,353 people per square kilometer, in line with high community mobility. According to Totok Tavirijanto, Head of the Surakarta City Statistics Agency (BPS), Surakarta's population density is 2.5 times higher than Semarang, the capital of Central Java Province, where the density is 4,400 people/km². "The population of Surakarta continues to grow due to births and a high rate of inward migration," he stated. The average temperature in Surakarta in 2016 ranged from 21.8°C to 33.1°C. According to 2019 BPS data, the monthly average temperature reached 35°C in November and ranged between 31°C and 34°C in other months, indicating a temperature increase from 2016 to 2019. Additionally, household electricity consumption increased from

349,722,372 kWh in 2018 to 366,780,634 kWh in 2019.

## METHOD

The research objects in this study are NDBI, NDVI, carbon emissions (household electricity), and the urban heat island effect in Surakarta City.

### A. Sampling Method

According to Sugiyono (2008), a sample is a part of the population that represents its characteristics. Stratified Random Sampling is used in the UHI study in Surakarta to ensure accurate representation of the city's diverse areas, such as the urban center, outskirts, and green zones, enabling a comprehensive analysis of temperature variations and UHI intensity across the city, which involves dividing the population into several homogeneous groups called strata, then randomly selecting samples from each stratum to represent each group. This method accommodates populations that are not uniform but can be grouped into relatively homogeneous categories, addressing sampling bias due to population diversity (Nurhayati, 2008, in Jannah, 2021). The samples in this study are differentiated based on UHI strata in five locations classified as very high, high, moderate, low, and very low. The sample size is calculated using the following formula (Sugiyono, 2010):

$$\eta = \frac{Population\ of\ group\ (stratum)}{Total\ Population} \text{ x Total Desired Sample (1)}$$

### B. Data Processing Techniques

The data processing steps in this study are as follows:

1. Radiometric Correction (DN to TOA Radiance and Reflectance): Radiometric and atmospheric corrections are applied to reflective channels, and Brightness Temperature is extracted from the thermal channel (band 10) in QGIS. Landsat 8 images are processed by selecting "Brightness Temperature in Celsius" and applying DOS 1 Atmospheric Correction.
2. TOA Radiance Conversion to Brightness Temperature: Brightness Temperature represents the thermal intensity emitted by an object, derived from spectral emissions in the thermal channel (Chander et al., 2007). Conversion from Celsius to Kelvin is done using the formula: BT = (b10 + 273.15) (BT=Brightness Temperatur; B10=band10)
3. NDVI Calculation: NDVI estimates vegetation density in an area and is calculated using band 4 (Red) and band 5 (Near-Infrared) as follows: $\text{NDVI} = \frac{\text{NIR}-\text{RED}}{\text{NIR}+\text{RED}}$ (NDVI=normalized difference vegetation index; NIR=Near-Infrared-Band 5; RED=Red-Band 4).
4. NDBI Calculation: NDBI helps identify built-up areas using the following formula. $\text{NDBI} = \frac{\text{b6}-\text{b5}}{\text{b6}+\text{b5}}$ (NDBI=Normalized Difference Built-up Index; B6=Band 6-shortwave Infrared 1/SWIR1; B5=Band 5-Near Infrared/NIR).
5. Emissivity Calculation (E): land Surface Emissivity (E) minimizes errors in surface temperature estimation, using processed vegetation index values. E = 0,004 x PV + 0,0986 (E=Evapotranspiration; PV=Proportional Vegetation).
6. LST Calculation: LST is the surface temperature of an object exposed to sunlight, derived from Brightness Temperature velues.
   $$\text{LST} = \frac{\text{b10}}{1+\left(\frac{10,8\ x\ b10}{14388}\right)\log\ (b1)}$$
   (LST=Land Surface Temperature)

8. UHI Calculation: UHI is extracted from LST values.
   UHI = Tmean – (μ+0,5α)
   (UHI=Urban Heat Islam Intensity; Tmean=Mean Temperature; μ=Baseline rural temperature; 0,5α=Adjustment Factor)

## C. Carbon Emission Processing

Carbon footprint calculations are based on field interview data, using stratified random sampling based on UHI classification. $CO_2$ emissions are calculated using household electricity consumption (kWh) and the IPCC (2006) formula:

$CO_2$ Emissions = FE × Electricity Consumption

Emission factors for $CO_2$, defined by the Ministry of Energy and Mineral Resources Directorate General of Electricity (2016, are as follows:

**Table 2**. Electricity Emission Factor

| Fuel type | Emission factor (ton $CO_2$/kWh) |
|---|---|
| Electricity | 0,000794 |

Electricity consumption data are collected monthly in rupiah units, with the current kWh rates varying across different PLN customer categories, as projected in Table 2.1 3.

**Table 3.** Electricity Tariff Price per kWh

| No | Category | Voltage | Price |
|---|---|---|---|
| 1 | Category R-1 | Low Voltage (TR) 900 VA | Rp 1,352 per kWh |
| 2 | Category R-1 | TR 1,300 VA | Rp 1,444.70 per kWh |
| 3 | Category R-1 | 2,200 VA | Rp 1,444.70 per kWh |
| 4 | Category R-2 | TR 3,500-5,500 VA | Rp 1,444.70 per kWh |
| 5 | Category R-3 | TR 6,600 VA and above | Rp 1,444.70 per kWh |
| 6 | Category B-2 | TR 6,600 VA-200 Kva | Rp 1,444.70 per kWh |
| 7 | Category B-3 | Medium Voltage (TM) above 200 Kva | Rp 1,444.70 per kWh |
| 8 | Category I-3 | TM above 200 Kva | Rp 1,444.70 per kWh |
| 9 | Category I-4 | High Voltage (TT) 30,000 kVA and above | Rp 996.74 per kWh |
| 10 | Category P-1 | TR 6,600 VA-200 Kva | Rp 1,444.70 per kWh |
| 11 | Category P-2 | TM above 200 Kva | Rp 1,444.70 per kWh |
| 12 | Category P-3 | TR for public street lighting | Rp 1,444.70 per kWh |
| 13 | Category L | TR, TM, TT | Rp 1,644.52 per kWh |

## D. Correlation and Regression Tests

Simple Correlation is a statistical technique used to measure the strength of the relationship between two variables and to identify the quantitative association between them. The strength of the relationship is assessed to determine if it is strong, weak, or non-existent, while the form of the correlation can be either positive linear or negative linear. In this study, simple correlation tests are conducted between UHI and NDVI, UHI and NDBI, UHI and LST, and UHI and carbon emission footprint. The simple correlation test uses Y (UHI) as the dependent variable and X (LST, NDVI, NDBI, carbon emission footprint) as independent variables.

Multiple Regression is a model that represents the equation between one dependent/response variable (Y) and two or more independent/predictor variables (X1, X2, ... Xn). The purpose of multiple regression testing is to predict the value of the dependent/response variable (Y) if the values of the independent/predictor variables (X1, X2, ... Xn) are known. It is also used to understand the relationship between the dependent variable and the other independent variables. The multiple regression equation is expressed as:

$$Y = \alpha + b_1.x_1 + b_2.x_2 + ..... + bn.xn$$

Where:
Y = Dependent variable (value to be predicted)
α = Constant
b1, b2, ..., bn = Regression coefficients
x1, x2, ..., xn = Independent varibles

Multiple regression is conducted on NDVI, NDBI, carbon emission footprint, and UHI, with UHI as the dependent variable (°C) and NDVI, NDBI, and carbon emission footprint ($CO_2$) as independent variables. Data for correlation and regression analysis are gathered using the fishnet tool in ArcGIS and processed using SPSS.

## E. Data Analysis Method

Data analysis is performed using two methods: spatial descriptive-comparative analysis and multiple correlation and linear regression.

1. Descriptive Analysis
   Descriptive analysis is used to explain the spatial distribution of vegetation density, buildings, carbon emission footprint, and UHI in Surakarta City. In the spatial distribution process, ArcGIS is utilized to map and analyze the geographic patterns of these variables. ArcGIS enables the creation of thematic maps, hotspot analysis to identify areas with high UHI intensity, and the calculation of spatial indices such as NDVI for vegetation and NDBI for built-up areas. With geostatistical analysis features, ArcGIS also supports deeper interpretations of the relationships between variables across different locations in Surakarta City.
2. Correlation and Regression Anlysis
   Correlation analysis aims to determine the magnitude of the relationship between one variable and another, specifically the relationship between X and Y variables. The variables used include NDBI, NDVI, and carbon emission footprint with UHI in Surakarta City. The multiple correlation coefficient indicates the strength of the relationship between two variables. In conducting descriptive statistical analysis, each variable must meet the requirements of normally and linearly distributed data.
3. Multiple Linear Regression is a model that describes the relationship between one dependent variable (Y) and two or more independent variables (X1, X2, X3, ..., Xn). The purpose of multiple linear regression testing is to predict the value of the dependent variable (Y) if the values of the independent variables are known and to understand the direction of the relationship between the dependent and independent variables.

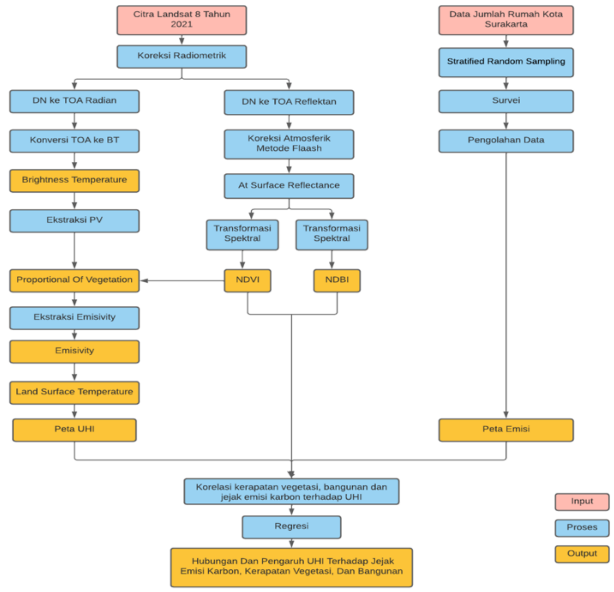


**Figure 1.** Research Flowchart

## RESULT AND DISCUSSION

The distribution of carbon emission footprints based on UHI classes was conducted using interpolation. The results of this interpolation indicate that the carbon emission footprint in Surakarta is low. Based on field data processing, Surakarta contributes approximately 8.708 tons of $CO_2$ from household electricity emissions, distributed across five classes in Figure 2.

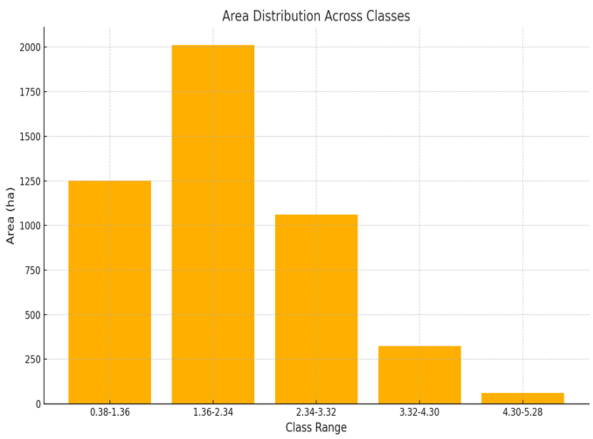


**Figure 2.** Area Distribution Across Classes

The low-emission class represents the largest emission distribution area, while the very high-emission class represents the smallest area. The sample point map can be seen in Figure, and the carbon emission footprint distribution map is shown in Figure 3.

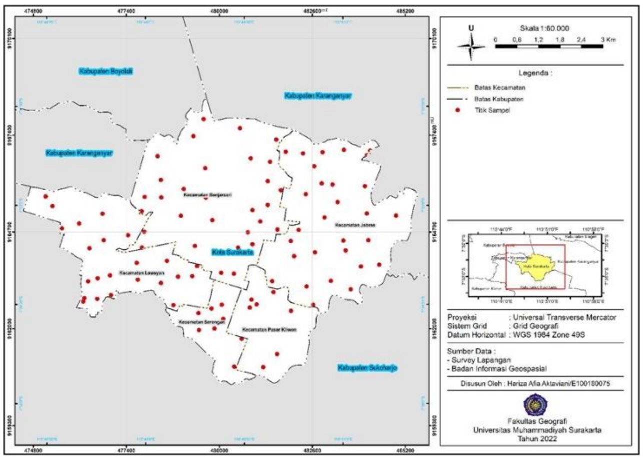

**Figure 3.** Sample Point Map

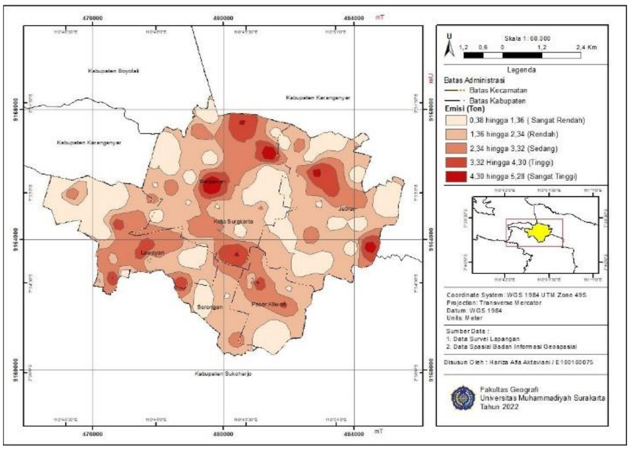

**Figure 4.** Carbon Emission Footprint Distribution Map

The distribution of vegetation, measured through NDVI (Normalized Difference Vegetation Index), has a significant relationship with Urban Heat Island (UHI) intensity. Vegetation absorbs solar radiation and reflects less heat energy compared to artificial surfaces like asphalt or concrete, making areas with dense vegetation cooler. Through the process of evapotranspiration, vegetation also naturally cools surface temperatures. In Surakarta, the uneven distribution of vegetation leads to variations in UHI intensity, with urban centers having sparse vegetation exhibiting higher temperatures compared to greener suburban areas. Enhancing vegetation cover, such as through urban parks or green corridors, can significantly reduce UHI intensity, creating cooler and more environmentally friendly microclimates in urban areas. was derived from Landsat 8 imagery classification using ENVI software. The vegetation distribution pattern in Surakarta Regency shows a generally even spread across regions, with varying coverage by district. Vegetation density distribution varies across districts: Banjarsari is dominated by low-density vegetation classification with 63.15%, non-vegetation at 13.46%, very dense at 3.42%, moderately dense at 19.10%, and water bodies at 0.87%, indicating very limited vegetation in Banjarsari. Non-vegetated land in Jebres District is lower at 11.84%, with low-density vegetation at 55.31%, very dense at 9.06%, moderately dense at 22.93%, and water bodies at 0.85%.

Laweyan District has a low-density vegetation distribution of 66.64%, non-vegetation at 10.97%, very dense at 2.10%, moderately dense at 19.60%, and water bodies at 0.69%. Pasar Kliwon District has low-density vegetation at 65.47%, non-vegetation at 15.79%, very dense at 4.72%, moderately dense at 13.00%, and water bodies at 1.01%. Lastly, Serengan District shows a low-density vegetation distribution of 67.03%, non-vegetation at 18.14%, very dense at 1.00%, moderately dense at 12.78%, and water bodies at 1.04%. The vegetation density distribution is illustrated in Figure 4.1. Based on the map below, the highest vegetation area is in Jebres District, covering 125.87 ha, while the highest non-vegetated area is in Serengan District, covering 55.48 ha.

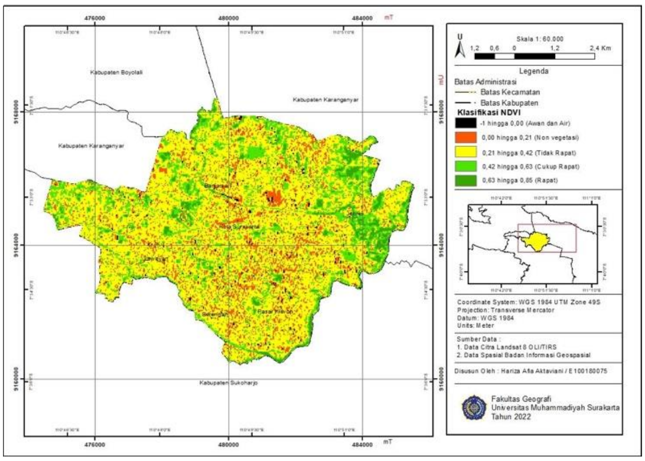


**Figure 5.** Vegetation Map

The NDBI (Normalized Difference Built-Up Index) was processed from Landsat 8 imagery and classified into four categories: low-density residential, high-density residential, very high-density residential, and non-residential, with a general distribution pattern dominated by residential land. Each district in Surakarta City shows different percentages in building density distribution. In Banjarsari District, the percentages are 39.01% low-density residential, 24.92% high-density residential, 10.70% very high-density residential, and 35.37% non-residential. In Jebres District, low-density residential covers 31.47%, high-density residential 28.44%, very high-density residential 0.98%, and non-residential 39.12%. Laweyan District has 35.73% low-density residential, 31.09% high-density residential, 1.20% very high-density residential, and 31.98% non-residential. Pasar Kliwon District has 29.23% low-density residential, 46.22% high-density residential, 2.08% very high-density residential, and 2.08% non-residential. Lastly, Serengan District has 33.86% low-density residential, 48.54% high-density residential, 48.54% very high-density residential, and 16.18% non-residential. Based on the map and the percentages, Serengan District, with the highest building density and 16.18% non-residential areas, experiences a significant increase in surface temperatures due to the dominance of built-up areas and limited green spaces. The dense concentration of buildings reduces the potential for heat dissipation and increases heat retention, intensifying the Urban Heat Island (UHI) effect and creating a warmer microclimate. In contrast, Banjarsari District, despite having the largest non-residential area at 39.12%, may experience relatively cooler temperatures in certain zones, depending on the presence of vegetation or open spaces within its non-residential areas. The stark difference in building density highlights how urban planning directly influences microclimatic conditions, with Serengan requiring interventions like green roofs or urban greenery to mitigate its high heat levels.

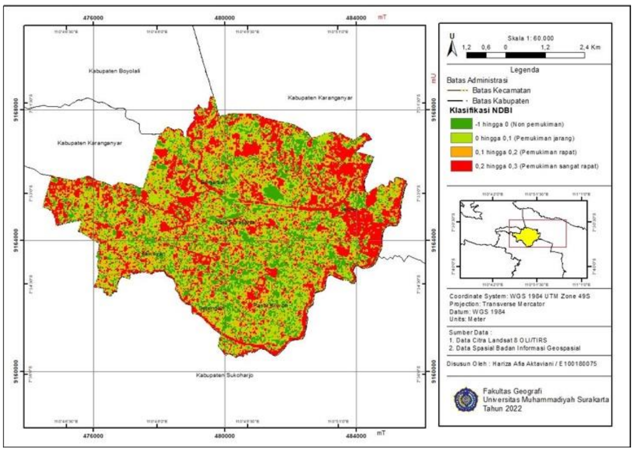


**Figure 6.** Building Density Map

In figure 6 explain the elationship between carbon emission footprint, vegetation density, and building density on uhi in surakarta city. Correlation analysis was used to evaluate the relationship between the carbon emission footprint, vegetation density (NDVI), and building density on Urban Heat Island (UHI) intensity in Surakarta City. The results showed a moderate negative correlation between UHI and NDVI, with a correlation coefficient of -0.434. This indicates that areas with higher vegetation density tend to have lower UHI intensity, while areas with low vegetation coverage or dense building distribution tend to experience higher UHI intensity, exacerbated by carbon emissions from human activities and the dominance of less environmentally friendly building layouts.

This negative coefficient indicates an inverse relationship, where an increase in UHI is associated with a decrease in NDVI values. The double asterisk (**) denotes a significant correlation at the 1% significance level (0.01). The significance value (Sig. 2-tailed) is 0.000, which is less than 0.05, confirming a significant relationship between UHI and NDVI. The correlation between UHI and NDBI also indicates a moderate strength of association, with a positive correlation coefficient of 0.453. This positive value means that as UHI increases, NDBI also increases. The significance value (Sig. 2-tailed) is 0.000, indicating a significant relationship between UHI and NDBI.

In contrast, the correlation between UHI and Emissions shows a very weak association, with a correlation coefficient of -0.112. This weak and inverse relationship suggests that an increase in UHI is not strongly influenced by Emissions. The significance value (Sig.) is 0.266, which is greater than 0.05, indicating no significant relationship between UHI and Emissions.

**Tabel 4.** Guideline for Interpreting Correlation Coefficients Regardless of Direction

| Interval Koefisien | Tingkat Hubungan |
|---|---|
| 0,00 – 0,199 | Sangat Lemah |
| 0,20 – 0,399 | Lemah |

| | |
|---|---|
| 0,40 – 0,599 | Sedang |
| 0,60 – 0,799 | Kuat |
| 0,80 – 1,000 | Sangat Kuat |

The relationship level between NDBI and UHI is moderate, with a coefficient of 0.453, meaning that as NDBI increases, UHI also increases. The relationship between NDVI and UHI has a coefficient of -0.434, also indicating a moderate relationship; as NDVI decreases, UHI increases. The emission value of -0.112 indicates a very weak relationship.

The regression coefficient of NDBI on UHI is 4.456, and the emission coefficient on UHI is -0.103. The significance value for NDBI is 0.00, meaning it is less than 0.05, indicating that NDBI has an influence on UHI—when NDBI increases, UHI also increases. The significance value for emissions is 0.328, which is greater than 0.05, indicating no influence between UHI and emissions. Based on the regression modeling results, the empirical formula for UHI (°C) is:

UHI = -0,634 + (4,456 x NDBI) + (-0,103 x Emissions)

The constant/intercept of -0.634 mathematically indicates that if the values of independent variables X1 and X2 are zero, then Y is -0.634. In other words, the UHI temperature without NDBI and emissions is -0.634 degrees Celsius. The regression coefficient of the NDBI variable (X1) is 4.456, meaning that an increase in NDBI, assuming other variables remain constant, will result in a temperature increase of 4.456 degrees Celsius. The emission regression coefficient (X2) of -0.103 means that an increase in emissions, assuming other variables remain constant, will result in a temperature decrease of -0.103 degrees Celsius.

The regression coefficient of NDVI on UHI is -3.892, and the emission coefficient on UHI is -0.037. The significance value for NDVI is 0.00, meaning it is less than 0.05, indicating that NDVI has an influence on UHI—when NDVI increases, UHI decreases. The significance value for emissions is 0.732, which is greater than 0.05, indicating no influence between UHI and emissions. Based on the regression modeling results, the empirical formula for UHI (°C) is:

UHI = 0,746 + (0,037 x Emissions) + (-0,3,892 x NDVI)

The constant/intercept of 0.746 mathematically indicates that if the values of the independent variables X1 and X2 are zero, then Y is 0.746. In other words, the UHI temperature without emissions and NDVI is 0.746 degrees Celsius. The regression coefficient for the emission variable (X1) is 0.037, meaning that an increase in emissions, assuming other variables remain constant, will result in a temperature increase of 0.037 degrees Celsius. The regression coefficient for NDVI (X2) of -3.892 indicates that every one-unit increase in NDVI will reduce the temperature by 3.892 degrees Celsius, assuming other variables remain constant. This value reflects a strong negative relationship between vegetation density and temperature, where dense vegetation, indicated by high NDVI values, reduces temperatures through photosynthesis and evapotranspiration processes. Conversely, areas with low NDVI values, such as built-up zones, tend to retain more heat, thereby increasing temperatures. This finding underscores the importance of vegetation cover in mitigating the Urban Heat Island (UHI) effect and creating cooler, more comfortable urban environments, particularly in densely populated cities like Surakarta. The values of NDVI and

NDBI have a strong influence on UHI, making it unsuitable to build a regression model involving both NDVI and NDBI as independent variables simultaneously, due to multicollinearity—an issue where there is a strong linear relationship between one predictor variable and another predictor variable within a regression model.

The spatial distribution of the Urban Heat Island (UHI) phenomenon in Surakarta City and its surroundings is presented as a map classified into four levels. The UHI classification is represented by colors ranging from white to red, with white indicating non-UHI areas, green for low UHI, yellow for moderate UHI, and red for high UHI. High UHI levels in certain districts, such as Serengan and Pasar Kliwon, can be attributed to high urbanization levels and the dominance of built-up areas, including commercial buildings, dense residential zones, and extensive road infrastructure. In contrast, areas with lower UHI levels, such as districts on the city's outskirts, have more extensive vegetation cover, including parks, agricultural lands, or other green spaces, contributing to natural cooling through evapotranspiration. This distribution highlights the direct relationship between land use patterns and UHI intensity, where areas with minimal vegetation cover and high building density tend to become UHI hotspots. Thus, mitigation efforts such as increasing green spaces and promoting more sustainable land use management are crucial to reducing UHI intensity in Surakarta.

Banjarsari District is predominantly a non-UHI area, with 73.11% non-UHI, 25.81% low UHI, and 1.09% moderate UHI. Jebres District has 68.44% non-UHI, 29.70% low, 1.86% moderate, and only 0.01% high UHI. Laweyan District has 58.40% non-UHI, 40.41% low, and 1.19% moderate UHI. Pasar Kliwon District shows 34.07% non-UHI, 58.67% low, 6.69% moderate, and 0.57% high UHI. Serengan District has 44.16% non-UHI, 54.04% low, and 1.80% moderate UHI. The spatial distribution of UHI in Surakarta City shows that Serengan District has the highest intensity, with surface temperatures up to 4.2°C above the city average due to 85% building density and minimal green space. In contrast, Banjarsari District, with 35% vegetation cover, has the lowest UHI intensity, with most of its area classified as non-UHI. Effective vegetation management in Banjarsari, such as urban parks and green corridors, can serve as a model for UHI mitigation in other areas. Policies like increasing green spaces in Serengan and controlling development in densely built-up areas are expected to effectively reduce UHI intensity.

## CONCLUSIONS

The research findings highlight that Surakarta City contributes 8,708 tons of $CO_2$ emissions from household electricity use, distributed across five districts. Serengan District accounts for the largest share of emissions, contributing 2,415 tons of $CO_2$, followed by Jebres District with 2,051 tons, Laweyan with 1,735 tons, Banjarsari with 1,628 tons, and Pasar Kliwon with 879 tons. This distribution aligns with variations in population density and electricity consumption patterns across districts.

The relationship between carbon emissions and UHI, though weak (coefficient: -0.112), underscores the indirect impact of emissions. Higher emissions often correlate with densely built-up areas lacking vegetation, which amplifies surface temperatures and intensifies the UHI effect through increased energy demand for cooling.

This finding indicates the need for energy efficiency measures and renewable energy adoption, particularly in districts with high emissions like Serengan.

Spatially, Serengan District experiences the highest UHI phenomenon, attributable to its dense building distribution and minimal vegetation cover (55.48 ha non-vegetated area). In contrast, Banjarsari District, with extensive vegetation coverage and the largest non-residential area (39.12%), experiences the lowest UHI intensity. To mitigate UHI, practical recommendations include enhancing urban greenery, such as rooftop gardens and urban parks in high-risk districts like Serengan, and replicating Banjarsari's effective vegetation management in other districts. Policies promoting sustainable land use and integrating renewable energy strategies are essential to reduce emissions and manage UHI effectively across Surakarta.

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