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Exploring the Relationship of Vegetation Density and Land Cover on the Urban Heat Island Phenomenon in Coblong, Bandung

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Abstract

The Urban Heat Island (UHI) phenomenon can occur naturally in urban areas due to increasing population density and built-up spaces, leading to higher temperatures compared to surrounding non-urban areas. This study investigates the UHI phenomenon in Coblong, Bandung, by analysing land surface tenperature (LST), vegetation density, and land cover data from 2017, 2019, and 2021 through remote sensing analysis using Landsat imagery data. The results reveal significant surface temperature disparities of 7 to 8 degrees Celcius between densely populated areas in the south and greener areas in the north of Coblong. The findings confirm the presence of the UHI effect and underscore the complexity of factors influencing it, including the distribution and density of vegetation. To mitigate this phenomenon, we propose a multifaceted approach that includes enhancing and strategically distributing green vegetation and employing innovative, more permeable construction materials for urban infrastructure. This strategy aims to reduce the UHI impact and improve thermal comfort and livability in Coblong and might be applied to other areas with similar characteristics facing similar challenges.

Keywords: *land cover; remote sensing; urban heat island; vegetation density*

1. Introduction

Urbanization refers to the process of becoming urbanized or the creation of urban areas, associated with the growth in the percentage of the population residing in urban spaces and the development of a settlement into a city. Essentially, urbanization involves a shift in the proportion of the population living in urban areas, where the rate of urban population growth exceeds that of rural population growth (Nuissl & Siedentop, 2012; Pontoh & Kustiwan, 2018). A report from UN-Habitat in 2022 states that in 2020, 56.2% of the world's population resided in urban areas, and this number is expected to continue increasing to reach 68.4% by the year 2050 (United Nations Human Settlement Programme, 2022). Urbanization, in its process, brings significant changes to the spatial planning and land use in urban areas, associated with population growth and the increasing need for built space, including housing and settlements, infrastructure, as well as other public and social facilities required to support human needs. One of the derivative impacts of the continuous change in land use is the increase in surface temperatures in urban areas. This is partly because the built environment in urban areas absorbs and converts solar energy into convectional (sensible) heat, resulting in higher temperatures compared to the surrounding rural areas where vegetation allows for the transformation of solar energy into latent heat (Stache et al., 2022). This phenomenon of higher surface temperatures in urban areas is known as the Urban Heat Island (UHI). UHI is a phenomenon where an urban area or zone tends to have a higher temperature compared to its surrounding areas, generally due to the high thermal capacity of building materials combined with a reduction in the quantity of open and green spaces in urban environments (Jumari et al., 2023). UHI presents a real challenge to urban life. In addition to affecting human comfort, increasingly hotter air and more frequent heatwaves in an area result in a

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heightened burden on healthcare facilities, particularly for vulnerable urban populations such as the elderly, children, and other susceptible groups (United Nations Human Settlement Programme, 2022). The UHI effect is also associated with an increased incidence of heat stress/heat stroke, exhaustion, and heightened suicidal tendencies (Singh et al., 2020; US EPA, 2024). Therefore, ongoing research on UHI is essential, given the profound impact of this phenomenon on community life, especially in urban areas.

Bandung, the capital of West Java Province, is experiencing rapid urbanization (Tarigan et al., 2016; Terang & Syafriharti, 2020). This is not only due to its status as the administrative center of West Java, but also because of various attractions that increase its population. One factor that can drive urbanization is the availability of opportunities for advancement, particularly in job differentiation or opportunity and education across various fields (Pontoh & Kustiwan, 2018). Coblong is one of 30 districts in Bandung and is a part of the rapidly developing Sub Wilayah Kota (SWK) Cibeunying area with a relatively high density according to the Bandung City Spatial Plan for 2022-2042. This growth is partly driven by the presence of several higher education institutions that attract residents from outside the region, such as the Bandung Institute of Technology (ITB) and Padjadjaran University (Unpad). Additionally, Coblong is also close to the West Java government center, which also serves as one of the activity hubs in Bandung. This proximity has made Coblong one of the most densely populated areas in Bandung, particularly in the Sedang Serang sub-district. However, despite its density, Coblong also has unique characteristics, with certain areas like Dago and Lebak Siliwangi sub-district having lower building density and higher vegetation cover. This condition makes Coblong an ideal location to directly observe how land cover is related to the UHI phenomenon prevalent in intra-urban level. Therefore, this paper aims to determine the relationship between land cover and the increase in urban temperatures in Coblong, Kota Bandung, to provide input for policy formulation related to environmental management and spatial planning in Bandung, especially in intra-urban level.

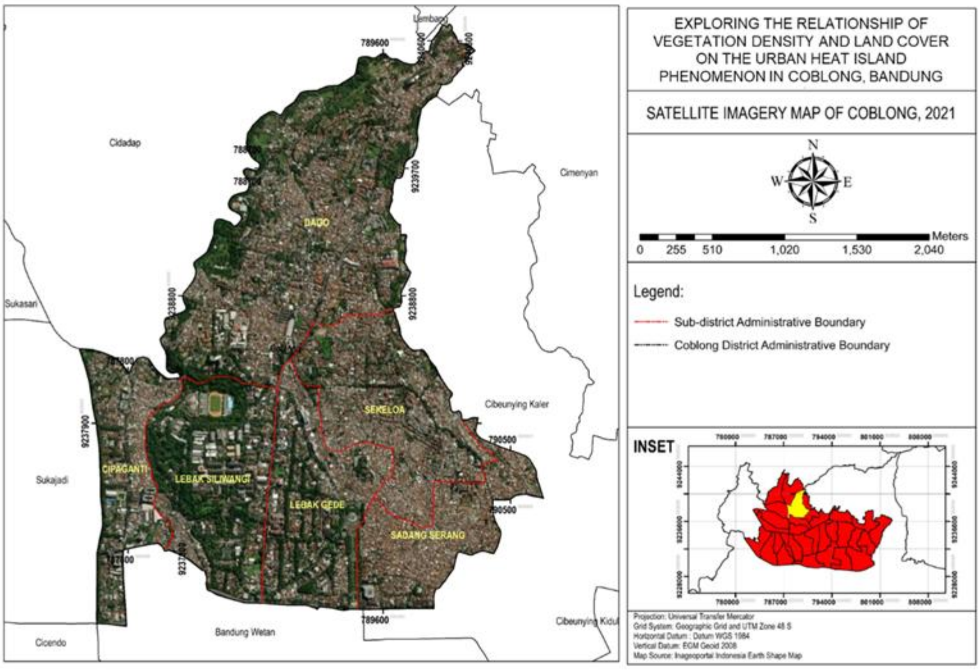

Figure 1. Satellite Imagery Map of Coblong, 2021
(Ina Geoportal Indonesia)

2. Literature Review

The Urban Heat Island, often referred to as UHI, is a phenomenon that has become a global issue in climate change. This phenomenon has been the focus of scientific research for more than two centuries, and despite its seemingly straightforward nature, significant confusion persists regarding its various types and how they are evaluated (Stewart & Mills, 2021). According to Siswanto et al., (2023), a city is experiencing the UHI effect when the inner city experiences much warmer temperatures than nearby rural areas. Due to the heat island effect, urban residents face greater risks compared to those in suburban or rural areas, and there is also a phenomenon where certain city neighbourhoods experience higher temperatures, known as "intra-urban" heat islands (US EPA, 2024). UHI is referred to as a "heat island" because the temperature distribution in a region forms a pattern similar to that of an island. The highest temperatures are typically observed at the core of this area, visually distinct from the cooler surrounding regions when illustrated spatially. An illustration showing the highest temperature contour at the center of the image, resembling a heat island, can be seen in the following image:

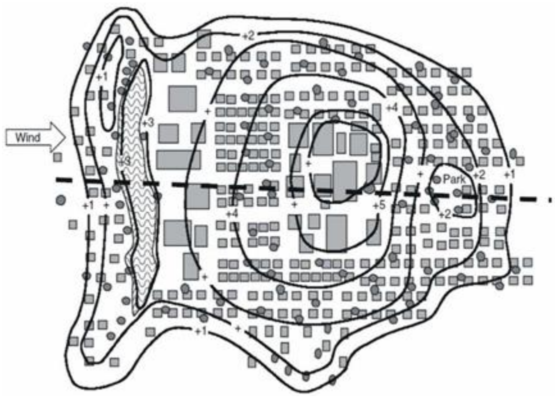

Figure 2. Illustration of UHI Phenomenon
(Voogt, 2002 in Maru et al., 2015)

The UHI phenomenon emerges due to marked temperature differences between urban center and their suburban or rural urban areas, resulting from accelerated urbanization (Liu et al., 2024). Various studies have shown that several factors can influence surface temperature in urban areas and the occurrence of the UHI phenomenon. These factors include changes in land cover, changes in urban vegetation, the types of building and urban infrastructure materials used, as well as the effects of anthropogenic heat, which is heat generated by human activities in the urban canopy layer (Ayuni et al., 2023; H. Chen et al., 2022; Liu et al., 2024; Rao et al., 2023; Vujovic et al., 2021; Wang et al., 2018). This article will focus on discussing the UHI phenomenon occurring in Bandung City, based on the two most critical factors influencing UHI intensity identified by Liu et al., (2024), namely vegetation cover and land use type.

2.1 Land Use / Land Cover

Urbanization is closely associated with dynamics in land use and land cover (LULC), which in turn are linked to variations in land surface temperature (LST) and the intensity of UHI (Rao et al., 2023). Different types of land cover are known to have varying effects on surface temperatures, where the UHI effect has become more pronounced in areas experiencing rapid urbanization (X.-L. Chen et al., 2006). LST has been significantly influenced by built-up areas, particularly in regions where heavy industries are established (Rashid et al., 2022). In contrast, water bodies and forests possess the strongest mitigation capacity for UHI and should be preserved (H. Chen et al., 2022). LST is also found to be higher in open land areas, and lower in vegetated areas, since built-up land reflects more heat compared to vegetation (Jannah & Bioresita, 2023). In other words, preservation of natural resources such as water bodies and forest or vegetation is essential for counteracting the adverse thermal effects brought about by urbanization and other urban activities. Furthermore, it has been found that in cities with high population density, the influence of built-up areas on LST values is the highest and most positive compared to cities with medium and low population densities (Al Shawabkeh et al., 2024). Overall, these studies collectively emphasize the critical impact of land use and its changes on land surface temperature, demonstrating how different land uses can have varying effects on surface temperatures in those areas, ultimately influencing the urban heat island phenomenon.

2.2 Vegetation Cover and Density

Another crucial factor affecting surface temperatures and contributing to the UHI effect is the presence of vegetation in urban settings. Research in China has shown that during the summer months, Land Surface Temperature (LST) in tree-covered areas is approximately 2.23°C lower than in adjacent built-up areas. Conversely, during winter, the LST in these vegetated areas is generally higher than in built-up areas, suggesting an insulating effect of trees (Guo et al., 2023). While research in Jordan indicates that the impact of built-up areas on Land Surface Temperature (LST) values is significantly positive in cities with high population density, the same research also reveals that in cities with medium to low population densities, the effect of vegetation cover on LST values is more substantial (Al Shawabkeh et al., 2024). Additionally, it is known that trees can contribute to reducing LST by providing shade, releasing water vapor through transpiration, and absorbing significant amounts of latent heat (Guo et al., 2023). Furthermore, the leaf area density (LAD) per plant can influence temperatures in urban areas. It has been observed that altering the characteristics of the leaf area density (LAD) per plant in vegetated base areas—for example, transitioning from 4% to 60% tree coverage and from a low to a high LAD—resulted in reductions of approximately 3°C in daily average temperatures and 5.23°C in daily maximum temperatures (Esfehankalateh et al., 2021). However, merely increasing the LAD does not significantly reduce surface temperatures; this effort must be complemented by higher tree percentages, and greater surface albedos, which facilitate convective cooling through enhanced evapotranspiration and reduced solar absorptivity (Esfehankalateh et al., 2021).

3. Method

3.1 Data Collection

This research utilized secondary data for analysis, consisting of Landsat 8 imagery from the month of May in the years 2017, 2019, and 2021, obtained from the U.S. Geological Survey (USGS) website at http://www.usgs.gov/. The selection of Landsat imagery data from 2017, 2019, and 2021 was chosen to observe the development of surface temperature and land cover in terms of vegetation density and built-up land area in Coblong over the years.

3.2 Analysis

The analysis in this study utilized various methods through ArcGIS software, involving the conversion of band values in the imagery according to the analytical requirements for each variable. The variables used include Land Surface Temperature, Vegetation Index, and Land Cover. The analysis methods for each variable are detailed in the following section:

3.2.1 Land Surface Temperature

Land Surface Temperature (LST) is defined as a kinetic quantity, independent of wavelength, that represents the thermodynamic temperature of the skin layer of a given surface, i.e. a measure of how hot or cold the surface of the Earth would feel to the touch (Guillevic et al., 2018). There are several steps involved in obtaining surface temperature values from Landsat imagery data, including extracting the Digital Number (DN) from the thermal band to convert it into surface temperature values. In Landsat 8 imagery, the conversion of DN to spectral radiance values is calculated using the following formula:

$$L\lambda = M_L QCAL + A_L$$

Where:

$L\lambda$ = Spectral radiance of Band x in watts / (m^2 * ster * μm), where x is the band number
M_L = Band-specific multiplicative rescaling factor from the metadata (RADIANCE_MULT_BAND_x, where x is the band number)
$QCAL$ = Image pixel value (DN)
A_L = Band-specific additive rescaling factor from the metadata (RADIANCE_ADD_BAND_x, where x is band number)

Following the conversion of DN to spectral radiance values, the next step is to transform these spectral radiance values into Brightness Temperature values using the following formula:

$$T = \frac{K_2}{Ln\left(\frac{K_1}{L_\lambda}+1\right)} - 273{,}15$$

Where:

T = Brigthness Temperature (*Celcius*)
K_1 = Spectral Radiance Calibration Constant
K_2 = Absolute Temperature Calibration Constant (K)
$L\lambda$ = Spectral Radiance in watts / (meter squared * ster * μm)

Subsequently, the calculation of Land Surface Temperature (LST) is performed using the formula outlined below:

$$LST = \frac{T}{1 + \left(w * \frac{T}{\rho}\right) \ln(e)}$$

Where:

LST = Land Surface Temperature (Celcius)
T = Brightness Temperature
w = Wavelength of emitted radiance (11.5 μm)
ρ = h * c / σ (1,438 * 10-2 mK)
h = Planck's Constant (6.626 *10-34 Js)
c = Speed of light (2,998 * 108 m/s)
σ = Boltzman Constant (1.38 * 10-23 J/K)
e = Emissivity

3.2.2 Normalized Difference Vegetation Index (NDVI)

NDVI generally differentiates the vegetation from the nonvegetative areas (Shukla et al., 2021). NDVI varies from -1 to +1 the closer the value is to 1, the higher the density, the healthier the circumstances, and, in general, the better the vegetation conditions will be (Amani & Shafizadeh-Moghadam, 2023). In this research, we will interpret the NDVI index values based on the following table:

Table 1: Greenness Level Classification Based on NDVI Values

NDVI	Greenness Level
-1 - <0,03	Non-vegetation / Very Low
0,03 - < 0,25	Low
0,25 - <0,40	Medium
0,40 - 1	High

Source: Marwoto and Ginting, 2009 in Kusumaningrum et al., 2024

The NDVI calculation from Landsat 8 imagery data can be performed using the following formula:

$$NDVI = \frac{\rho NIR - \rho RED}{\rho NIR + \rho RED}$$

Where:
$NDVI$ = Normalized Difference Vegetation Index
ρNIR = Reflectance value of the near-infrared band
ρRED = Reflectance value of the red band

3.2.3 Land Cover (LC)
Land cover describes the types of features present on the earth's surface or its physical manifestation, while land use refers to the human activities or economic functions associated with a specific piece of land (Puttaswamigowda et al., 2013). This study will identify land cover types such as built-up areas and vegetation, and then examine their relationship with surface temperature changes. Land cover classification is conducted using the iso cluster unsupervised classification method. This method utilizes a combination of RGB (red, green, and blue) bands obtained from composite bands 1 through 8 (Alif & Firdaus, 2021). The results of the unsupervised classification in this study will produce two types of land cover: built-up areas and vegetation areas.

4. Results and Discussion

4.1 Land Surface Temperature (LST) Distribution Analysis

Based on the analysis of Landsat imagery from 2017, 2019, and 2021, it has been observed that there was an increase in land surface temperature in Coblong during this period. The lowest and highest temperatures in Coblong in 2017 were 23°C and 30°C respectively, which increased to 24°C and 32°C by 2021. From this data, it is evident that there was a maximum temperature rise of 2°C. Additionally, it was noted that there is a temperature difference of 7 – 8°C between the areas with the highest and lowest temperatures in Coblong. Areas with relatively higher temperatures are located in the southeast of Coblong, including Sedang Serang and Sekelola sub-district, known for their high population density within the district. In contrast, areas with relatively lower temperatures are observed in the northern and eastern parts, specifically in the Dago and Lebak Siliwangi sub-districts, characterized by less densely populated residential areas with a greater presence of trees and green spaces. The distribution of surface temperatures in Coblong District for the years 2017, 2019, and 2021 can be viewed in the Figure 3 below:

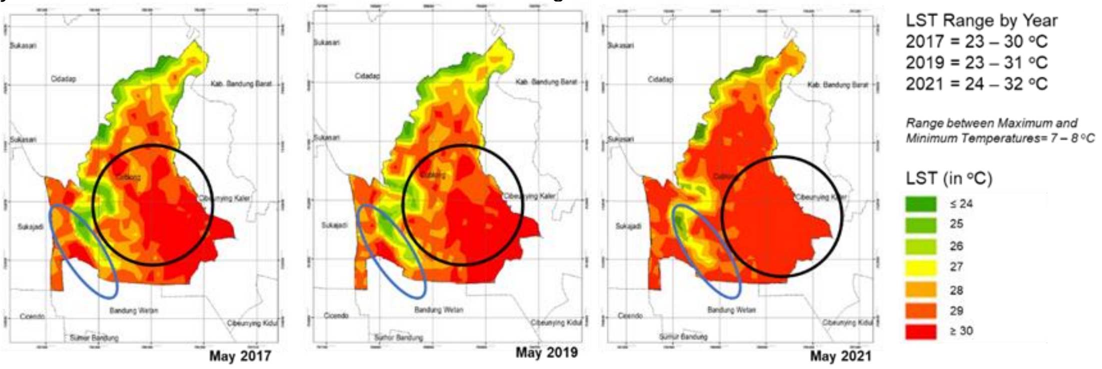

Figure 3. Land Surface Temperature (LST) Distribution in Coblong in 2017, 2019, and 2021 (Author's Analysis)

Based on the land surface temperature map shown in Figure 3, it is apparent that areas with relatively high surface temperatures have expanded, especially in the western or southeastern sections of Coblong, particularly in the densely populated residential neighbourhoods of Sedang Serang and Sekeloa This analysis of surface temperature distribution suggests that Coblong District exhibits characteristics of the UHI phenomenon, where areas with densely populated urban features consistently show higher temperatures compared to less densely populated surrounding areas, which have more green vegetation.

4.2 Normalized Difference Vegetation Index (NDVI) Analysis

The Normalized Difference Vegetation Index (NDVI) in Coblong District in 2017 showed a minimum value of -0.02 and a maximum of 0.46, with an average value of 0.22. Following years showed similar trends, with 2019 recording a minimum of -0.05 and a maximum of 0.50, with the average value consistently remaining at 0.22. In 2021, the minimum was -0.07 and the maximum was 0.51, with the average again at 0.22. The consistent average NDVI value of 0.22 across 2017, 2019, and 2021 suggests that there have been no significant changes in vegetation density in Coblong. The distribution of areas with different vegetation density classes is varied across different locations, as illustrated in the following map:

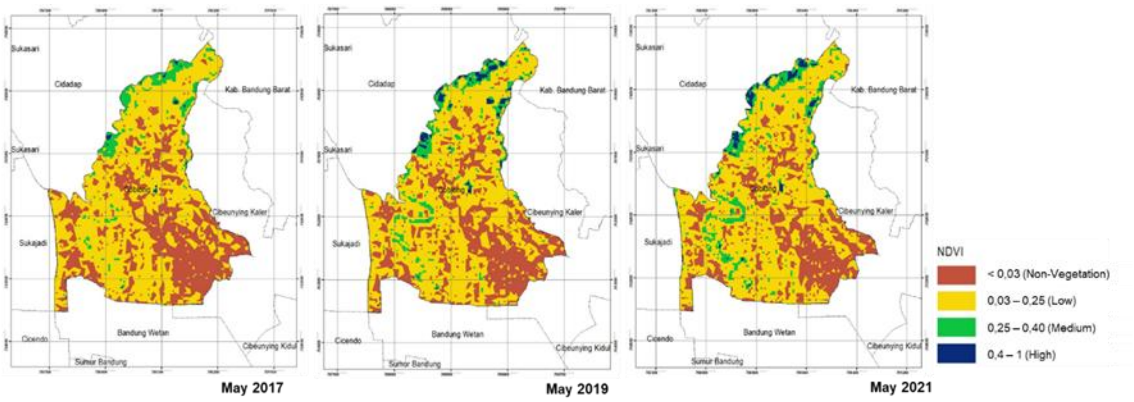

Figure 4. Normalized Difference Vegetation Index (NDVI) Distribution in Coblong in 2017, 2019, and 2021 (Author's Analysis)

Based on the series of maps in Figure 4, it can be seen that the vegetation density levels tend to remain constant. Additionally, it is observed that the majority of Coblong exhibits medium to low vegetation density levels while areas with high vegetation density are located on the northern and eastern sides of the district.

4.3 Land Cover (LC) Analysis

The Land Cover analysis from 2017, 2019, and 2021 indicates an expansion of built-up areas within Coblong. The more developed regions, predominantly composed of built-up areas, are primarily located in Sekeloa, Sedang Serang, and parts of Dago. In contrast, areas characterized by higher vegetation coverage are found in Lebak Siliwangi and Cipaganti. The Figure 5 below displays the land cover in Coblong District for the years 2017, 2019, and 2021, illustrating the year-to-year changes in land cover conditions.

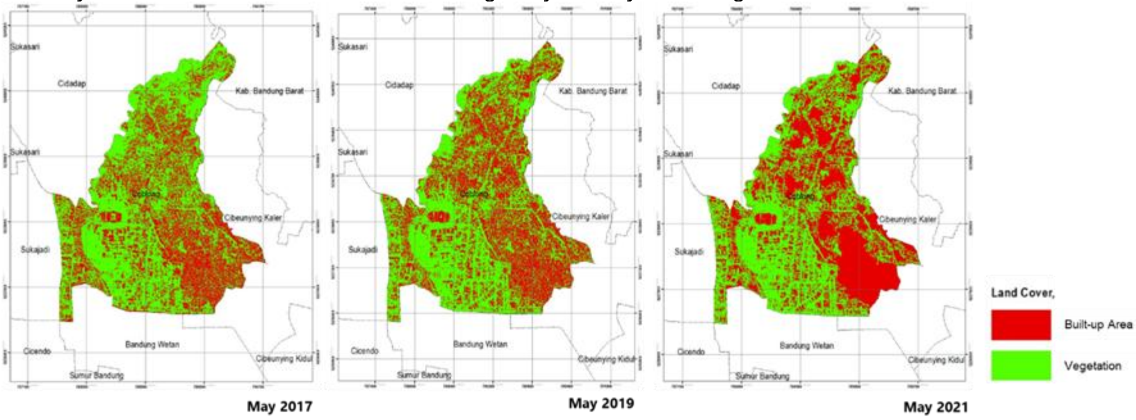

Figure 5. Land Cover (LC) Distribution in Coblong in 2017, 2019, and 2021 (Author's Analysis)

4.4 Discussion

The analysis of land surface temperature, vegetation density, and land cover in Coblong indicates that it experiences the urban heat island phenomenon, where surface temperatures in densely populated urban areas are relatively higher compared to other areas. Spatially, it can be seen that built-up and non-vegetated areas in Coblong, which characterize urban settings, have relatively higher temperatures compared to vegetated areas, particularly those with high vegetation density. These findings align with previous research which has shown that built-up areas tend to have higher surface temperatures compared to their surroundings with lower building density and have more vegetation (Al Shawabkeh et al., 2024; H. Chen et al., 2022; Jannah & Bioresita, 2023; Rashid et al., 2022).

Meanwhile, based on the analysis of vegetation density (NDVI), areas with high vegetation density experienced an increase from 2017 to 2019 and 2021. This trend occurred in parts of the northern area of Dago, which has been characterized by medium to high vegetation density from the outset, thus the expansion of high-density vegetation was concentrated in the same areas or locations. When compared with the rise in surface temperatures, these findings are somewhat inconsistent with several previous studies, as the increase in surface temperatures occurred even as vegetation density increased. This inconsistency may partly be attributed to the fact that the increase in density was localized to specific areas, such as the northern part of Dago. However, this inconsistency might also stem from the limitations of Landsat imagery, which only captures the surface appearance from above and is unable to account for land cover beneath the canopy or the actual number of plants and trees present, or even obscured by cloud or cloud shadows (Cao et al., 2023; Wijedasa et al., 2012). It may also incorrectly classify moss coverage on water bodies as vegetation (Aydin et al., 2024). Since NDVI is analyzed based on specific spectrum reflections by leaves and plants, the number and condition of foliage can greatly influence the resulting NDVI values. In the case of Coblong, the NDVI values may be affected by increasingly healthy plants reflecting the spectrum perceived as high density, while in reality, it may not be an increase in the number of plants but rather an increase in denser and healthier foliage. Accordingly, in line with the research by Esfehankalateh (2021), simply increasing leaf quantity is insufficient to counteract the UHI effect, it must be complemented by increased tree percentages and high surface albedos, which enhance convective cooling through evapotranspiration processes and reduce solar absorptivity. However, it should also be noted that despite the overall temperature rise, surface temperatures in areas identified as having dense vegetation coverage remained lower compared to areas with lower vegetation density. Furthermore, the temperature increase in areas of high vegetation density tends to be slower compared to non-vegetated areas, highlighting how vegetation plays a crucial role in maintaining lower surface temperatures compared to other areas in Coblong.

Additionally, the analysis results demonstrate how densely populated residential areas in Coblong, like Sadang Serang, exhibit relatively higher surface temperatures compared to other parts of the district. This finding underscores the pronounced effect of urban density on microclimate, particularly how high density built-area can significantly elevate local temperatures, contributing to the UHI effect in these neighborhoods. This effect is further supported by the research of Al Shawabkeh et al. (2024), which reveals that built-up areas have a more pronounced impact on temperatures in regions with higher population densities. This finding highlights the need for targeted urban planning and green infrastructure strategies in densely populated areas to mitigate temperature rise and improve urban living conditions, particularly in high density population area.

The discussion above opens a dialogue on how the UHI effect influences urban planning, including at a micro scale such as vegetation management and city infrastructure planning. As mentioned in the introduction, the UHI effect significantly impacts urban communities, from increasing energy burdens due to indoor air conditioning use to reducing comfort during activities and causing other health and environmental effects. Therefore, it is critical to consider the adaptation strategies that urban areas and communities can employ to mitigate the UHI effect. One of the most effective strategies to mitigate the UHI effect is to increase greenery in urban landscapes, as it is evident that green areas can reduce the impact of UHI. This involves selecting species that not only thrive in urban conditions but also contribute effectively to cooling through processes such as shading and evapotranspiration. Tree species considered beneficial are those with high CO2 absorption rates, optimal transpiration rates even under non-optimal conditions, rapid growth, high biomass accumulation, and longevity (Devianti, 2020). As discovered in this study, the vegetation in Coblong, particularly those areas with high density, is concentrated in only a few regions, resulting in lower surface temperatures also being confined to those specific points. This uneven distribution can limit the broader benefits of cooling and environmental quality across the entire district. Furthermore, it is essential to ensure that vegetation is optimally distributed and not concentrated solely in specific areas. Therefore, contemporary innovations such as urban farming can also be utilized to optimize vegetation distribution in densely built areas to reduce the UHI effect in those regions. This aligns with previous research which states that urban gardens can help reduce the heat island effect by creating thermal comfort, reducing flood risk and water runoff, and conserving energy (Humaida et al., 2023). Additionally, permeable pavements have recently garnered significant attention as a method to improve urban microclimates by lowering surface temperatures through evaporative cooling, offering advantages over conventional concrete pavements due to their lower reflectivity, heat capacity, and thermal conductivity, and their ability to absorb more heat due to increased porosity (Vujovic et al., 2021). Building on this, another strategy that governments can adopt is the use of permeable materials in existing infrastructure, especially in densely populated areas, to mitigate the effects of the UHI experienced by residents.

5. Conclusion and Recommendation

5.1 Conclusion

Based on the analysis conducted, it can be concluded that the Urban Heat Island (UHI) phenomenon is present in Coblong, Bandung, as evidenced by surface temperature differences reaching 7 to 8 degrees Celsius between densely populated areas in the south and greener areas in the north. The spatial distribution of vegetation, particularly in areas like the northern part of Dago, has shown a correlation with lower surface temperatures, demonstrating the potential of green vegetation and infrastructure to mitigate UHI effects. However, the findings also underscore the complexity of the UHI phenomenon, where increased vegetation density alone does not uniformly reduce surface temperatures across all areas. The effectiveness of vegetation in cooling urban environments is influenced by its distribution, density, and the types of species planted. This emphasizes the need for strategic urban planning that integrates comprehensive green infrastructure, not just in terms of increasing the quantity but also enhancing the quality and distribution of urban green spaces.

5.2 Recommendation

Tackling the UHI effect in Coblong requires a multifaceted approach that not only aims to increase and optimize green cover but also ensures its equitable distribution across the district. Integrating new materials and technologies for urban construction is crucial for enhancing thermal comfort in urban areas and improving overall livability, given the significant impact of UHI on various aspects of human life. Future strategies should focus on creating a more equitable distribution of green spaces and infrastructure, ensuring that all areas, especially those with high population densities, benefit from reduced UHI effects and enhanced environmental conditions. This comprehensive approach will contribute to making Coblong a more sustainable and resilient urban environment. On the other hand, this study relies solely on satellite imagery data processing as the data and information basis for analysis. Therefore, future research should consider integrating data from direct field observations to better understand phenomena that satellite imagery cannot capture. Future research should also explore socio-economic aspects potentially related to UHI, such as policy dynamics and human activities, to provide a more holistic understanding of the drivers behind UHI.

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