Indonesian Journal of Multidisciplinary Sciences (IJoMS)
Vol. 5 No. 1 2026, 831-844
E-ISSN: 2963-7635 | P-ISSN: 2986-2426
Publisher: CV. Era Digital Nusantara

Assesment of Thermal Comfort Dymamics in Central Java Province Using Era 5 Reanalysis Data

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ARTICLE INFO

Article History
Submission : 26-05-2026
Received : 27-05-2026
Revised : 10-06-2026
Accepted : 13-06-2026

Keywords
Central Java Province;
Discomfort Index;
ERA 5;
Thermal Comfort

DOI:
10.59066/ijoms.v5i1.2489

ABSTRACT

Central Java experiences high population density and increasing anthropogenic activities that potentially alter microclimatic conditions and decrease human thermal comfort. This study analyzes the spatial and temporal variations of thermal conditions across the province during 2017–2025. Air temperature and relative humidity data were obtained from the ERA5-Land reanalysis dataset and processed using Google Earth Engine. Thermal conditions were evaluated using the Discomfort Index (DI), while validation was carried out through comparison with in-situ observations from the Badan Pusat Statistika (BPS). The findings reveal a gradual increase in DI throughout the study period, indicating a decline in environmental comfort levels. Temporally, January recorded the highest DI due to elevated humidity, whereas October showed relatively more comfortable conditions. Spatial analysis demonstrates that highland regions consistently experienced lower DI compared to lowland and coastal areas, emphasizing the important role of elevation in shaping thermal conditions. Validation results confirm that ERA5-Land data are reliable for examining thermal comfort patterns in Central Java.

Introduction

With a population density of 1,113 people per square kilometer and an annual growth rate of 0.99%, Central Java Province is considered one of the more densely populated regions in Indonesia (Badan Pusat Statistik, 2025a). High population density and growth rates are directly proportional to increased anthropogenic activities such as massive infrastructure development and increased energy consumption (Kartika et al., 2021). These activities will lead to increased carbon emissions, which will contribute to rising air temperatures (Wuebbles et al., 2003).

Central Java Province has experienced an annual increase in air temperature of 0.014°C or around 0.051% (Kusumawardhani & Gernowo, 2015). Based on research, this increase in air temperature has the potential to reduce thermal comfort levels, increase the risk of heat-related health problems, air pollution, and excessive water and energy consumption (Şahingöz & Berberoğlu, 2023). In tropical climates, thermal comfort for performing activities is generally in the range of 22°-28°C with humidity around 70-80%. This condition is based on the assumption that the temperature in Indonesia reaches a range of 35°C with 80% humidity (Sitanggang et al., 2021).

Thermal comfort can be assessed based on human subjective perception or through an objective approach using bioclimatic parameters (Sofan et al., 2024). In general, thermal comfort is influenced by various meteorological factors, such as air temperature, relative humidity, wind speed, and solar radiation, which together determine human physiological responses to thermal environmental conditions (Briegel et al., 2024). The interaction between these variables plays a role in shaping the level of comfort or discomfort felt by individuals during activities (Fajrini & Latifah, 2018). Therefore, the assessment of thermal comfort through an objective approach can be done using various quantitative methods, one of which is the Discomfort Index (DI) method, which uses air temperature and relative humidity as the main parameters in its calculations (Thom, 1959). However, studies on the spatial and temporal dynamics of thermal comfort on a regional scale in Central Java Province are still limited, especially those utilizing reanalysis data. Therefore, this study aims to analyze the dynamics of thermal comfort in Central Java Province using the Discomfort Index (DI) method based on ERA5 reanalysis data.

Method

Research Location

This study was conducted in the administrative region of Central Java Province, located in the central part of Java Island, Indonesia. Geographically, Central Java Province is located at coordinates 5°40' - 8°30' South Latitude and 108°30' - 111°30' East Longitude, including Karimunjawa Island. Based on data from a class I climatological station in Semarang City, Central Java Province has an average air temperature ranging from 28.2°C to 30.0°C with an average humidity varying from 67% to 84%. The highest rainfall recorded was 3,413.7 mm3, with the highest number of rainy days around 220 days (Badan Pusat Statistik, 2025c).

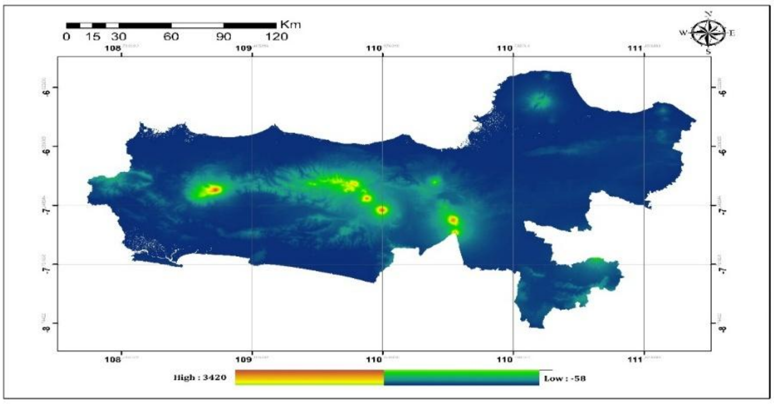

Figure 1. Research Location Map

Data Collection

The data used in this study are monthly average air temperature data from the ERA5 reanalysis for 2017-2025 in Central Java Province and monthly dew point temperature data from the ERA5 reanalysis for 2017-2025 in Central Java Province. The researchers also used air temperature and relative humidity data for Central Java Province based on the years 2017-2025 from the Central Java Province in Figures Central Statistics Agency 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025b as supporting data.

Reanalysis Era 5 Data

The ERA5-Land data used in this study was obtained from ECMWF through the Copernicus Climate Data Store. This dataset is a reanalysis product resulting from the integration of various atmospheric observation data sources (Kartika et al., 2021). Data with a spatial resolution of approximately 11 km was used as the main input in calculating the Discomfort Index (DI) and processed using the Google Earth Engine (GEE) platform.

Table 1. List of Data Use in Research

Parameter	Time Range	Spatial Resolution	Source	Benefit in Research
Air Temperature	Annual, 2017-2025 (Central Java Province)	-	Badan Pusat Statistika	Data validation from ERA 5 Reanalysis
Relative Humidity	Annual, 2017-2025 (Central Java Province)	-	Badan Pusat Statistika	Data validation from ERA 5 Reanalysis
2m *Air Temperature*	Hourly, 2017-2025 (Central Java Province)	11 km	*ECMWF Climate Reanalysis, Copernicus Climate Data Store*	Air temperature estimates from ERA 5
2m *Dewpoint Temperature*	Hourly, 2017-2025 (Central Java Province)	11 km	*ECMWF Climate Reanalysis, Copernicus Climate Data Store*	Relative humidity estimates from ERA 5

Source: Author

Thermal Comfort

Thermal comfort analyzed from an objective perspective through bioclimatic calculations can be determined using various methods that have been developed (Hidayati & Banja, 2018), one of which is the Discomfort Index (DI). This index is used to assess thermal comfort conditions in outdoor environments because it provides fairly accurate and relevant information, particularly in studies of comfort and energy efficiency (Poupkou et al., 2011). In this study, the DI calculation according to Thom was performed using the following equation (Thom, 1959) :

$$DI = \left[\frac{T_d+T_w}{2}\right] + 0.1[150 - (T_d + T_w)] \quad (1)$$

Description :

T_d = Wet bulb dry temperature (°F)
T_w = Wet bulb temperature (°F)

The formula was then simplified and modified using the air temperature and relative humidity formula (Psiloglou, Gkinis, & Giannakopoulos, 2025).

$$DI = T_a - 0.55(1 - 0.01RH)(T_a - 14.5) \quad (2)$$

Description :
T_a = Air Temperature (°C)
RH = Relative Humidity (%)

In processing air humidity data using the dew point value T_d found in ERA 5 reanalysis data using the formula (Lawrence, 2005) :

$$RH = 100 - 5(t - t_d) \quad (3)$$

Description :
RH = Relative Humidity
T = Air Temperature
T_d = Dew Point

Table 1. Classification of Discomfort Index Values

Discomfrt Index Value Range	Description
DI < 21	Comfort
21 ≤ DI <24	Less than 50% people feel discomfort
24 ≤ DI < 27	More than 50% people feel discomfort
27 ≤ DI < 29	Some resident feel discomfort
29 ≤ DI < 32	Everyone experience intense heat stress
DI ≥ 32	Medical emergency

Table 2 presents the classification of the Discomfort Index (DI) as an objective indicator of thermal comfort used in the study. This classification is used as a reference in interpreting the level of thermal comfort based on the DI value (Siami & Ramadhani, 2019).

Dynamic Discomfort Index

The discomfort index dynamics are analyzed to observe changes in thermal comfort temperature values over time. Temporal analysis will be conducted by dividing the period into three stages: the initial period, the transition period, and the current period. The initial period will start from 2017-2019, the transition period will be from 2021-2022, and the current period will start from 2023-2025.

Correlation between ERA 5 Reanalysis Air Temperature and BPS Data

Pearson's correlation analysis was used to examine the relationship between ERA5 reanalysis air temperature and air temperature based on data from the Central Statistics Agency (BPS) in Central Java Province during the period 2017–2025. This analysis aims to assess the level of suitability and consistency of ERA5 reanalysis data in representing regional air temperature variations compared to statistical data as reference data. The results of this correlation analysis are then used as a supporting basis in interpreting the results of the spatial and temporal analysis of the Discomfort Index in the study area.

Results and Discussion

The validation results demonstrate that ERA5-Land data provide relatively reliable representations of regional climatic variability in Central Java Province, particularly for air temperature variables. The strong positive correlation between ERA5-Land air temperature and BPS observational data indicates that the reanalysis dataset is capable of representing regional temperature conditions with relatively good accuracy. Similar findings were reported by Yilmaz (2023), who explained that ERA5-Land datasets are able to reproduce long-term temperature variability effectively for climatological analysis.

Despite the relatively strong correlation, several differences in absolute temperature values remain visible between ERA5-Land data and observational data, with temperature deviations reaching approximately 3–4°C in certain periods. These discrepancies are likely associated with differences in spatial representation between reanalysis datasets and station-based observations. ERA5-Land data represent averaged atmospheric conditions within grid cells with a spatial resolution of approximately 0.1° (around 11 km), whereas BPS observational data reflect localized environmental conditions measured directly at climatological stations. Consequently, local environmental characteristics such as land cover heterogeneity, urban heat accumulation, vegetation density, cloud cover variability, and topographic complexity may not be fully represented by the reanalysis dataset. Similar findings were also reported by Muñoz-Sabater et al. (2021), who explained that ERA5-Land products tend to spatially average local climatic variability, particularly in heterogeneous tropical environments.

Compared to air temperature validation, humidity validation demonstrated weaker statistical performance. Relative humidity conditions are highly dynamic and strongly influenced by localized environmental processes such as rainfall intensity, evapotranspiration, vegetation density, and soil moisture conditions. According to Park et al. (2025), ERA5 datasets often underestimate humidity variability in tropical environments because atmospheric moisture conditions are spatially heterogeneous and highly sensitive to local climatic interactions. As a result, humidity variability is generally more difficult to represent accurately than air temperature variability using regional-scale reanalysis products.

Spatial analysis indicates that northern coastal and lowland regions consistently experienced higher Discomfort Index (DI) values than mountainous regions throughout the observation period. Coastal areas such as Tegal, Pekalongan, Demak, Rembang, and Pati remain more vulnerable to thermal discomfort because of their relatively high air temperatures and humid atmospheric conditions. According to Lawrence (2005), high atmospheric humidity reduces evaporative cooling efficiency from the human body, thereby intensifying perceived heat stress. Similar findings were also reported by Siami & Ramadhani (2019), who found that increased atmospheric humidity during wet monsoon periods significantly intensifies discomfort index values in tropical environments.

The relatively high DI values identified in northern coastal regions may also reflect the influence of urbanization and land surface modification. Urban regions such as

Semarang, Pekalongan, and Demak are characterized by extensive built-up land cover dominated by asphalt surfaces, concrete structures, industrial zones, transportation infrastructure, and dense settlements. Impervious surfaces tend to absorb and retain solar radiation more efficiently than vegetated surfaces, increasing surface and near-surface air temperatures. Reduced vegetation cover further weakens evapotranspiration processes that naturally function as environmental cooling mechanisms. According to Silva et al. (2024), increasing impervious surface density and vegetation reduction significantly intensify thermal discomfort conditions in tropical urban environments. Similar conclusions were also reported by Ullah et al. (2024), who found that rapid urban expansion substantially increases thermal stress intensity in densely populated regions.

Conversely, mountainous regions such as Wonosobo, Temanggung, Banjarnegara, Magelang, and Salatiga consistently exhibited lower DI values and relatively more comfortable thermal conditions. These regions are characterized by higher elevation, lower air temperatures, and more extensive vegetation cover compared to coastal environments. According to Feng et al. (2020), air temperature generally decreases with increasing elevation because atmospheric pressure becomes lower at higher altitudes, resulting in adiabatic cooling processes. Vegetation conditions also contribute to environmental cooling through shading and evapotranspiration processes that help stabilize local microclimatic conditions. Similar findings were reported by Terschanski et al. (2024), who demonstrated that vegetation characteristics play an important role in regulating tropical microclimatic conditions and reducing thermal stress intensity.

Temporal analysis further indicates that seasonal climatic variability strongly influences thermal comfort dynamics in Central Java Province. January generally exhibited relatively high DI values due to elevated atmospheric humidity during the rainy season, while July showed relatively lower DI values associated with drier atmospheric conditions. In October, thermal discomfort conditions increased again because of the simultaneous influence of relatively high air temperature and increasing atmospheric humidity during the monsoon transition period. According to Pradana (2024), transitional monsoon periods in Indonesian urban environments are frequently characterized by simultaneous increases in temperature and atmospheric humidity, intensifying thermal discomfort conditions.

The gradual increase in DI values between 2017 and 2025 suggests a declining trend in thermal comfort conditions across Central Java Province. This tendency may be associated with regional warming processes combined with urban expansion and land cover changes occurring particularly in northern coastal regions. Similar conclusions were reported by Subedi et al. (2024), who found that long-term warming trends substantially alter outdoor thermal comfort conditions in humid tropical environments.

Air Temperature Validation Result

In this study, validation was carried out using air temperature data from the Central Java Provincial Statistics Agency (BPS) for 2017, 2018, 2019, 2020, 2021, 2022, 2023, and 2024. The results are as follows :

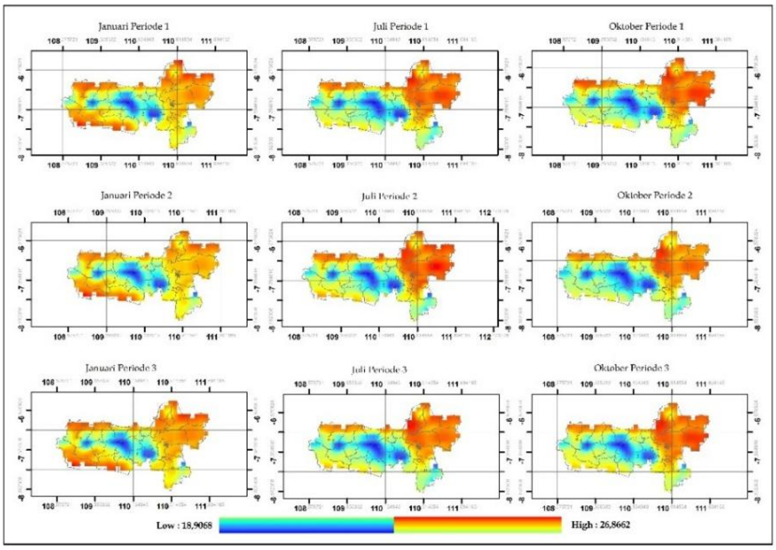

Figure 1. Air Temperature Distribution Map

Based on Figure 2, there is a significant difference between the air temperature resulting from the processing of ERA5 reanalysis data and the air temperature observed by the Central Statistics Agency (BPS) for the period 2017–2024. The air temperature resulting from the processing of ERA5 images shows a relatively more stable pattern with relatively small fluctuations between years. In contrast, the BPS observed air temperature data shows more varied dynamics with more significant annual fluctuations. This difference in characteristics indicates a difference in the ability of the two data sources to represent air temperature variations over time. Reanalysis data has a fairly good ability to represent temporal changes in air temperature on a regional scale.

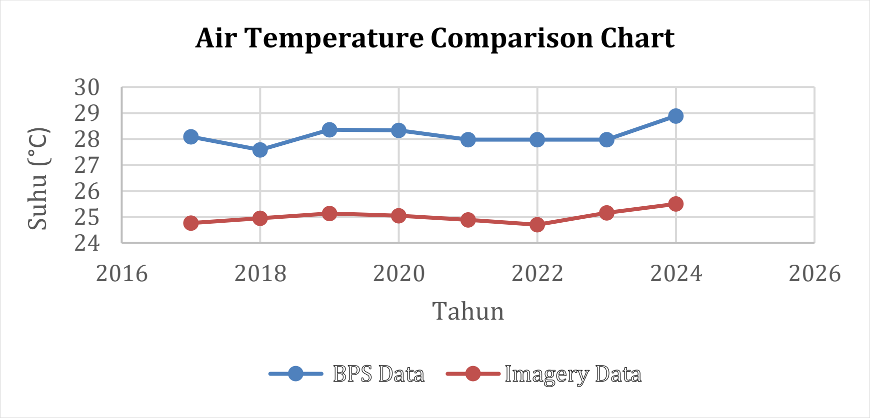

Figure 2. Comparison of Processed Air Temperature Images with In-situ Data

Based on Figure 3, the validation results between the air temperature from ERA5 image processing and the BPS in-situ air temperature produced a Pearson correlation coefficient value of 0.70, indicating a positive relationship with a strong level of strength. This indicates that the increase in air temperature observed in field observation data tends to be followed by an increase in air temperature in reanalysis data. This finding is in line with various studies showing that ERA5 reanalysis data is able to represent air temperature variation patterns and trends well on a medium to long scale.

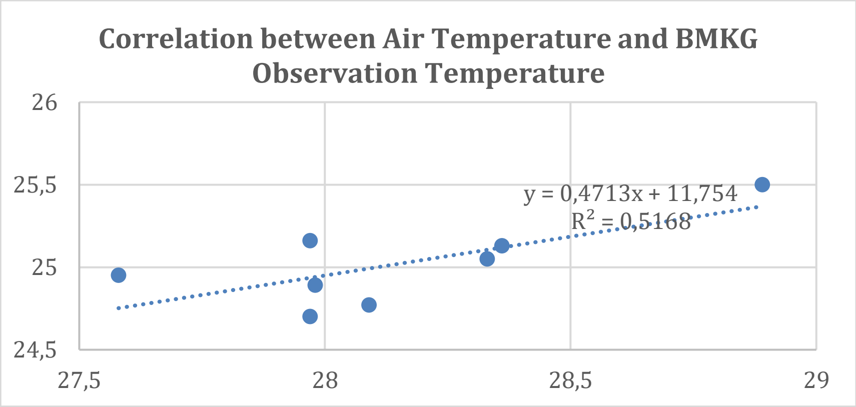

Figure 3. Linear Regression Results between Processed Image Air Temperature Data and In-situ Data

The coefficient of determination (R^2) value of 0.5168 indicates that approximately 51.68% of the variation in in-situ air temperature can be explained by the air temperature resulting from ERA5 image processing. The remaining variation is influenced by other factors that are not fully captured by the reanalysis data, such as differences in data collection times, local atmospheric conditions, spatial grid resolution, and surface heterogeneity. An R^2 value above 0.5 is still considered quite good for studies based on remote sensing and reanalysis data.

The correlation significance test produced a p-value of 0.044, which is less than the significance level of 0.05. Thus, the relationship between the ERA5 image air temperature and the in-situ air temperature is statistically significant, meaning that the correlation is not coincidental.

Humidity Validation Result

In this study, validation was carried out using air humidity data from the Central Java Provincial Statistics Agency (BPS) for 2017, 2018, 2019, 2020, 2021, 2022, 2023, and 2024. The results are as follows :

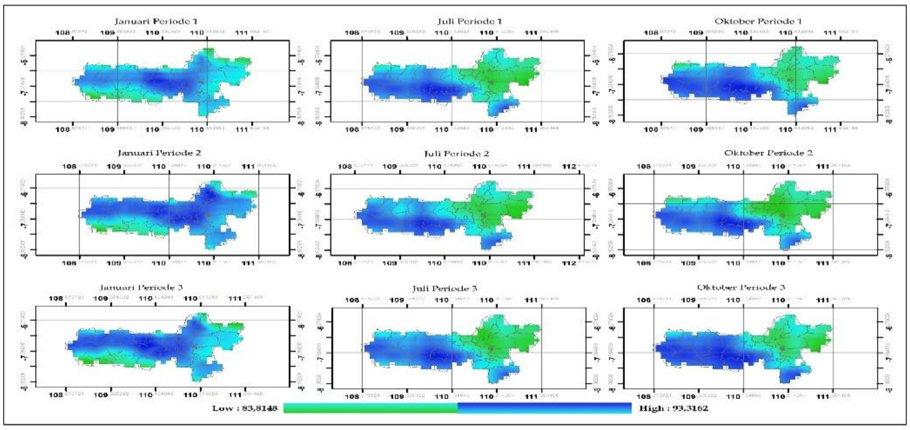

Figure 4. Air Humidity Distribution Map

Based on a comparison between air humidity data generated from image processing and in-situ data (BPS) for the period 2017–2024, it can be seen that both data sets show relatively similar fluctuation patterns, although there are differences in absolute values in some years of observation. In general, air humidity data generated from images tends to have higher values than in-situ data, indicating differences in measurement characteristics between the two data sources.

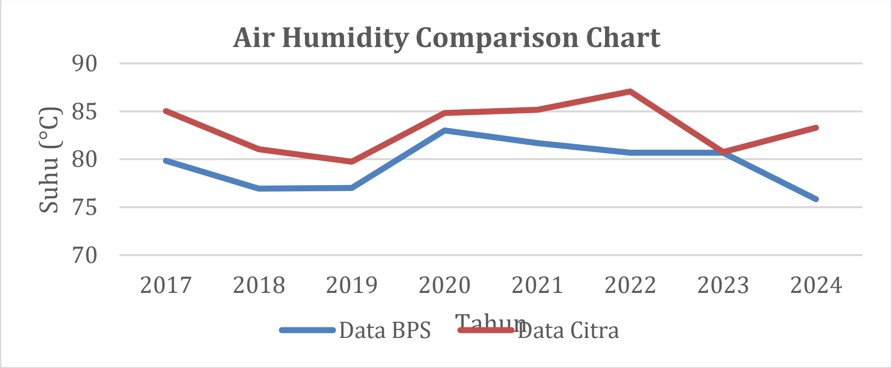

Figure 5. Comparison Chart of Air Humidity Processed from Images with In-situ Data

The Pearson correlation analysis resulted in an r value of 0.56, indicating a positive relationship with moderate strength between air humidity from imagery and in-situ data. This means that an increase in air humidity observed in the field tends to be followed by an increase in air humidity in the imagery data, although the relationship is not particularly strong. This shows that image data is able to capture general trends in air humidity changes, but with limited accuracy.

The correlation significance test produced a p-value of 0.07. This value is greater than the significance level of 0.05, so the relationship between the two data sets is not statistically significant at a 95% confidence level. However, a p-value close to 0.05 indicates a fairly significant relationship, especially when analyzed with a larger amount of data or at a more lenient significance level (α = 0.10).

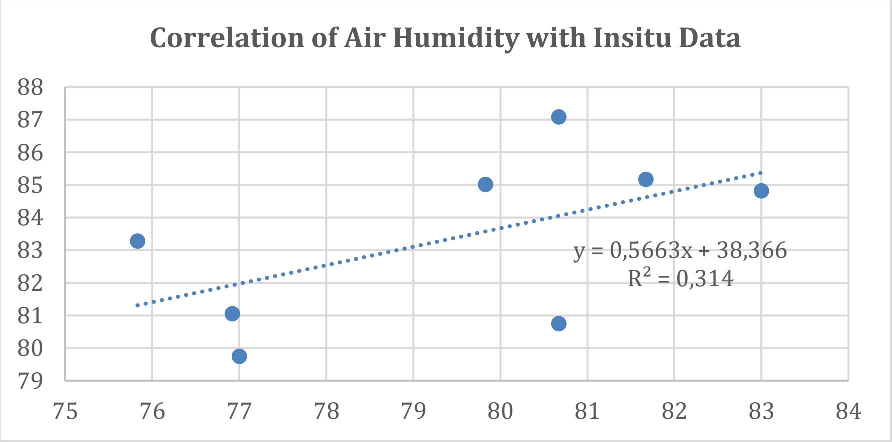

Figure 6. Linear Regression Results between Processed Image Air Humidity Data and Insitu Data

Linear regression analysis between air humidity data from imagery and in-situ data shows a coefficient of determination R^2 of 0.314, which means that approximately 31.4% of the variation in in-situ air humidity can be explained by the imagery data.

Discomfort Index

In January, which represents the peak of the rainy season, the Discomfort Index (DI) in Central Java Province shows higher thermal discomfort in coastal areas than in highlands. Coastal areas such as Tegal (25.58), Pekalongan (25.39), Rembang (25.24), Pati (25.11), and Blora (25.05) experienced the highest levels of discomfort, while highland areas such as Wonosobo (21.61), Temanggung (21.90), Magelang (21.92), Salatiga (22.06), and Banjarnegara (22.50) were relatively more comfortable. High air humidity during the rainy season intensifies the sensation of heat, so even though the air temperature does not reach its annual maximum, the heat pressure remains significant.

In the following period, despite fluctuations between periods, the spatial pattern of thermal comfort remained consistent. DI in coastal areas experienced a slight decrease, for example, Tegal (25.11), Pekalongan (24.87), Rembang (24.84), Pati (24.63), and Demak (24.63), but it remained higher than in highlands such as Wonosobo (21.26), Magelang (21.61), Salatiga (21.62), Temanggung (21.68), and Semarang (22.09). Thus, more than 50% of the population in the northern coast of Central Java experiences thermal discomfort, reflecting the relationship between high humidity during the rainy season and the influence of topography, as shown in Figure 8.

In July of periods 1, 2, and 3, thermal comfort conditions in Central Java showed a relatively consistent pattern across periods. Highland areas such as Wonosobo consistently had the lowest DI values, namely 20.69 in period 1, 20.95 in period 2, and 20.58 in period 3, which are classified as comfortable. Other regions such as Magelang, Temanggung, and Banjarnegara had DI values in the range of 21–24, indicating conditions where less than 50% of people were likely to feel uncomfortable. Conversely, coastal and lowland areas such as Tegal (25.18–25.37), Pekalongan (25.14–25.19), Demak (24.72–24.87), Rembang (24.76–24.89), and Pati (24.64–24.71) are in the $24 \leq DI < 27$ category, which theoretically indicates conditions where more than 50% of people are likely to experience thermal discomfort.

The interannual comparison shows that the DI value in July only experienced minor fluctuations and did not change categories significantly. This condition indicates that differences in thermal comfort are more influenced by regional characteristics than interannual variations. Regions with high DI values tend to maintain the same level of thermal discomfort from year to year, while regions with low DI values show relatively stable conditions. Thus, in July, thermal discomfort in Central Java tends to be persistent, especially in coastal areas, while highland areas are relatively more comfortable based on temperature and humidity indicators.

Based on the results of the Discomfort Index (DI) calculations for October periods 1, 2, and 3, the thermal comfort level in Central Java shows a consistent spatial pattern between periods, with DI values that are generally higher than in July. Highland areas such as Wonosobo continued to have the lowest DI values, namely 21.49 in 2017, 21.04 in 2021, and 21.49 in 2025. These values were in the range of $21 \leq DI < 24$, which indicates conditions where less than 50% of people are likely to feel uncomfortable. Other regions such as Magelang, Temanggung, Banjarnegara, and Salatiga are also in the same range, with DI values between 21.98 and 22.63, indicating relatively comfortable conditions even though the level of discomfort is starting to increase compared to highland areas.

Conversely, coastal and lowland areas consistently show high DI values and fall into the category of $24 \leq DI < 27$, which theoretically indicates conditions where more than 50% of people are potentially experiencing thermal discomfort. Tegal recorded the highest DI values throughout the entire period, namely 26.10 in 2017, 26.02 in 2021, and an increase to 26.12 in 2025. High DI values were also found in Pekalongan (25.96–26.05), Demak (25.75–25.88), Rembang (25.65–25.86), and Blora (25.62–25.78). The change in DI values between years in October was relatively small and did not change the thermal comfort category, indicating that thermal discomfort conditions in October tended to be persistent, especially in coastal areas, while highland areas remained at a relatively better level of comfort despite an increase in DI values compared to July.

Spatially, the areas with the highest Discomfort Index values are consistently found on the north coast of Central Java, covering Brebes, Tegal, Tegal City, Pemalang, Pekalongan, Pekalongan City, Kendal, Semarang City, Demak, Jepara, Pati, and Rembang. Lowland areas in the central part, such as Grobogan, Blora, Sragen, Sukoharjo, Klaten, and Wonogiri, show moderate DI values, indicating significant heat stress but not as high as in coastal areas. Conversely, highland and hilly areas such as Wonosobo, Banjarnegara, Temanggung, Magelang, Salatiga, Banyumas, and Purbalingga consistently show the lowest DI values throughout the observation period. This pattern is consistent with the spatial visualization in Figure 8, which shows a map of thermal comfort distribution in Central Java Province.

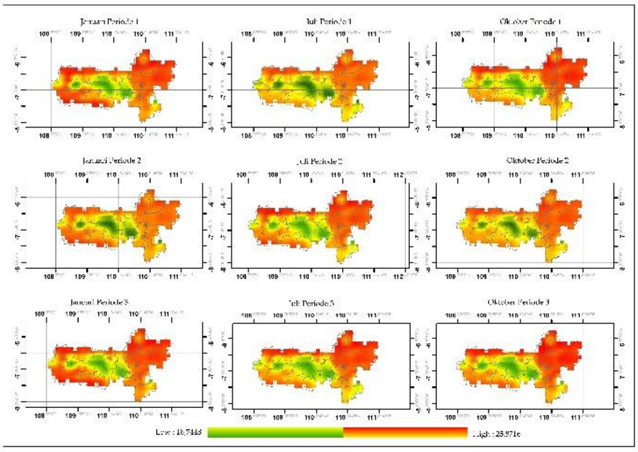

Figure 7. Map of Discomfort Index Distribution

The results and discussion are adjusted to the research approach. If the quantitative research approach consists of descriptive statistics, the results of the assumption test and the results of hypothesis testing are then analyzed critically. If the qualitative approach is in the form of themes from the results of the qualitative analysis carried out.

Conclusion

Based on the results of the Discomfort Index (DI) analysis for the 2017–2025 period, it can be concluded that thermal comfort conditions in Central Java Province have gradually declined. The increase in DI values from year to year indicates a downward trend in thermal comfort levels, although most areas are still in the mild to moderate discomfort category and have not yet reached extreme conditions. Temporally, January consistently shows the highest DI value due to the dominance of high air humidity during the rainy season, while October is the period with relatively better thermal comfort conditions due to the balance between temperature and air humidity.

Spatially, altitude has a significant effect on DI value variation. Highland areas consistently have lower DI values and more comfortable thermal conditions than lowland and coastal areas. This is related to lower air temperatures with increasing altitude and environmental characteristics that are relatively more conducive to thermal comfort. Conversely, lowland and coastal areas show higher DI values and a clearer upward trend, making these areas more vulnerable to a decline in thermal comfort.

This study has several limitations. The analysis relied on ERA5-Land reanalysis data with a spatial resolution of approximately 11 km, which may not fully represent local microclimatic variations, particularly in urban and mountainous areas. In addition, the Discomfort Index (DI) only considers air temperature and relative humidity, without including other meteorological parameters such as wind speed and solar radiation that may also influence thermal comfort conditions.

Future studies are recommended to use higher spatial resolution climate or remote sensing data and incorporate additional thermal comfort indices, such as PET or UTCI, to provide a more comprehensive assessment of thermal comfort dynamics. Further research may also examine the influence of land use change, urbanization, and vegetation cover on thermal comfort conditions in Central Java Province.

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