

IoT-Based Instrumentation for Urban–Rural Thermal Comfort Assessment Using Temperature Humidity Index

Muhammad Afif¹, Dibyo Susanto², Muchamad Rizqy Nugraha³, Achmad Fahrudin Rais⁴

^{1,2,3}Undergraduate Program in Applied of Instrumentation Meteorology Climatology Geophysics, State College of Meteorology Climatology and Geophysics (STMKG), Tangerang, Indonesia

⁴National Research and Innovation Agency (BRIN), Jakarta, Indonesia

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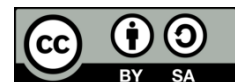
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ABSTRACT

Urbanization alters land surface characteristics and may contribute to the Urban Heat Island (UHI) effect, affecting outdoor thermal comfort. This study presents an Internet of Things (IoT)-based instrumentation system for microclimate monitoring and thermal comfort assessment using the Temperature-Humidity Index (THI). The system integrates calibrated DHT22 sensors, an ESP32 microcontroller, a 20×4 LCD, Firebase Realtime Database, and a web dashboard. Sensor calibration against BMKG reference instruments produced maximum deviations of -0.116°C for air temperature and -0.87% for relative humidity. The system was deployed simultaneously for 24 hours at an urban site in Kelurahan Tanah Tinggi and a rural site in Desa Cibodas, with 10-minute sampling intervals. Tanah Tinggi recorded a higher mean air temperature (29.05°C) than Cibodas (26.63°C), lower mean relative humidity (75.77% and 81.93%), and higher mean THI (27.59 and 25.57). Based on Wati and Fatkhuroyan (2017), the mean THI at Tanah Tinggi was classified as “Uncomfortable,” while Cibodas was “Partly Comfortable.” The cumulative distribution showed 58.33% “Uncomfortable” observations at Tanah Tinggi and 65.28% “Comfortable” observations at Cibodas. These results indicate an urban–rural thermal contrast consistent with an urban heat island pattern. However, interpretation is limited by the 24-hour period, two sites, and differences in elevation and local environmental conditions. The proposed system provides a low-cost approach for high-temporal-resolution microclimate monitoring and thermal comfort assessment.

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Corresponding Author:

Corresponding Muhammad Afif

Undergraduate Program in Applied of Instrumentation Meteorology Climatology Geophysics, State College of Meteorology Climatology and Geophysics (STMKG)

Tangerang, Banten, Indonesia

Email: afifbjm5nv.alghazi@gmail.com

1. INTRODUCTION

Rapid urbanization has significantly transformed urban land-surface characteristics by replacing natural vegetation and open areas with impervious surfaces such as asphalt, concrete, and rooftops. These changes can increase heat absorption and retention, contributing to the Urban Heat Island (UHI) phenomenon, in which urban areas tend to exhibit higher air temperatures than their surrounding rural areas [1]. A study of urbanization and surface urban heat islands (SUHIs) in western Java reported substantial urban expansion over the past two decades, accompanied by increasing land surface temperature and SUHI intensity. The study further identified anthropogenic heat flux and urbanization as positive contributors to SUHI intensity, while vegetation and water coverage contributed negatively [2]. Such thermal differences may affect outdoor human thermal comfort by increasing heat exposure and altering local microclimatic conditions [3].

Conventional microclimate monitoring commonly relies on Automatic Weather Stations (AWS) or standalone data loggers. Although these systems provide reliable measurements, their relatively high procurement and maintenance costs, limited spatial deployment, and operational requirements can constrain

their use for dense and real-time microclimate monitoring [4]. The development of Internet of Things (IoT) technology provides a cost-effective alternative by enabling automated data acquisition, wireless transmission, and remote monitoring [5]. However, low-cost sensors such as the DHT22 may be affected by measurement errors and environmental conditions. Therefore, laboratory calibration and appropriate correction procedures are important to improve measurement consistency and ensure the suitability of the sensor for field observations [22].

Previous studies have investigated the relationship between urban characteristics and microclimatic conditions. Reference [6] established the fundamental concept of UHI, explaining the role of urban materials and reduced vegetation in increasing heat retention, particularly during nighttime. Subsequent studies have reported that areas with greater vegetation coverage tend to exhibit cooler and more thermally comfortable conditions than densely built-up areas [7]–[10]. These findings highlight the importance of continuous measurements at the local scale to characterize thermal differences between urban and rural environments.

The Temperature-Humidity Index (THI) is a practical indicator for assessing thermal comfort because it incorporates air temperature and relative humidity into a single index [11]. Meanwhile, the availability of low-cost microcontroller platforms, such as the ESP32, and cloud-based services, such as Firebase, enables the development of IoT instrumentation for real-time environmental monitoring [12]. Previous research has demonstrated the application of DHT22 sensors and ESP32 microcontrollers for IoT-based temperature and humidity monitoring using platforms such as ThingSpeak [13]. An IoT wireless sensor network comprising 14 nodes was also used to monitor temperature and humidity differences between shaded green spaces and unshaded paved areas, demonstrating the feasibility of continuous and cost-effective microclimate monitoring [14]. In addition, Firebase-based IoT systems have been implemented for remote monitoring and smart-home applications [15].

Building upon these studies, this research develops and evaluates an IoT-based thermal monitoring instrument integrating a calibrated DHT22 sensor, ESP32 microcontroller, LCD display, Firebase database, and web dashboard. The system measures air temperature and relative humidity and calculates THI in real time for outdoor thermal comfort assessment. The instrument is deployed at an urban and a rural site to characterize their observed thermal contrast. Unlike studies focusing primarily on remote sensing or broader IoT sensor networks, this study emphasizes the instrumentation design, sensor calibration, real-time data transmission, and field implementation of a low-cost IoT system for localized thermal monitoring.

Accordingly, this study aims to design and implement an IoT-based instrumentation system for measuring air temperature and relative humidity, calculating THI, and assessing urban–rural thermal differences. The results are intended to demonstrate the applicability of low-cost IoT instrumentation for high-temporal-resolution microclimate and thermal comfort monitoring. Because the field comparison involves only two sites and a limited observation period, the observed thermal contrast is interpreted as consistent with an urban heat island pattern rather than as a definitive quantification of UHI intensity.

2. MATERIALS AND METHODS

2.1. System Flowchart

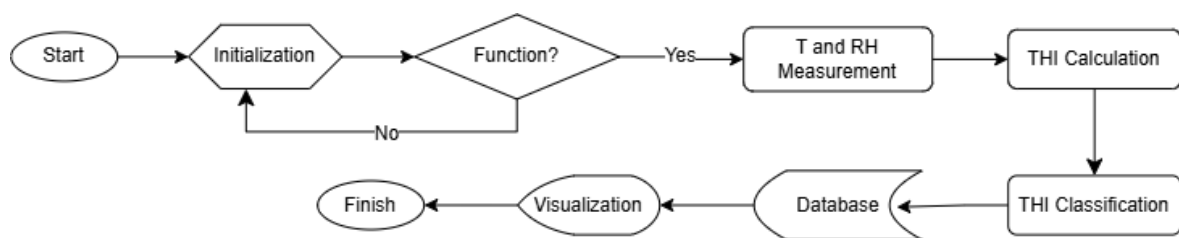


Fig. 1. System Flowchart

The developed IoT instrumentation system operates through a continuous sensing, processing, transmission, and visualization cycle, as illustrated in Fig. 1. The main operational stages are as follows:

1. **System Initialization:** The ESP32 microcontroller initializes hardware peripherals (DHT22 sensor, 20x4 I2C LCD) and establishes network connectivity via the Wi-Fi/MiFi module to configure the Firebase cloud environment.
2. **Connectivity & Diagnostic Verification:** The system continuously verifies network and sensor operational status; if a connection failure or hardware error occurs, an error alert is displayed on the local LCD, and the system attempts to re-initialize the link automatically.
3. **Data Acquisition:** The DHT22 measures ambient air temperature (T) and relative humidity (RH).

4. **THI Index Computation:** The measured temperature and relative humidity are corrected using the calibration parameters obtained from laboratory calibration. The corrected values are then used to calculate the Temperature-Humidity Index (THI).
5. **Thermal Comfort Classification:** The calculated THI value is classified according to the thermal comfort boundaries adopted in this study [20].
6. **Local Display:** The corrected temperature, relative humidity, THI, and thermal comfort classification are displayed on the 20×4 I2C LCD.
7. **Cloud Data Transmission:** The ESP32 packages the measurement parameters into a JSON payload and transmits the data to the Firebase Realtime Database.
8. **Web Visualization and Sampling Cycle:** The stored data are displayed on the web dashboard through real-time charts and tables. After the predefined sampling interval, the system repeats the measurement cycle.

2.2. Hardware Design

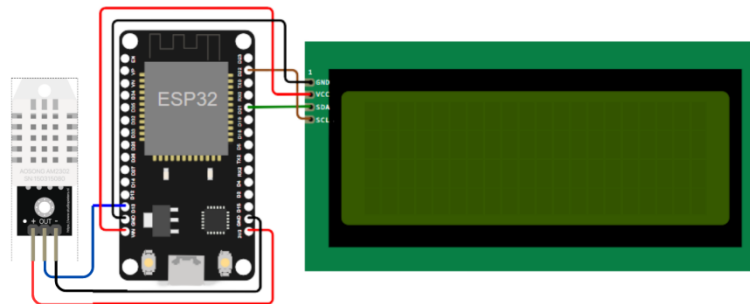


Fig. 2. Circuit Schematic

The hardware consists of an ESP32 microcontroller, DHT22 temperature and relative humidity sensor, and 20×4 I2C LCD. The DHT22 is connected to the ESP32 using 3.3 V for the supply, GND for the ground connection, and GPIO 13 (D13) for the data signal. The I2C LCD is connected to GND, VIN, GPIO 21 (SDA), and GPIO 22 (SCL), respectively, as shown in Fig. 2.

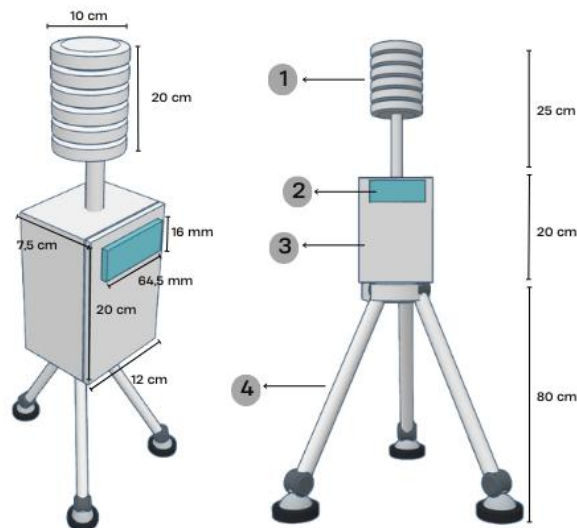


Fig. 3. Hardware Design

The physical instrument was designed to support outdoor measurements while protecting the sensing and electronic components from direct environmental exposure. As shown in Fig. 3, the system consists of four main components: (1) a Stevenson screen to reduce direct solar radiation exposure to the sensor, (2) an LCD frame for local data visualization, (3) an enclosure containing the ESP32 and electronic components, and (4) a tripod supporting the measurement assembly.

2.3. Software Design

The software system consists of the ESP32 firmware, Firebase Realtime Database, and web dashboard. The ESP32 performs sensor acquisition, data correction, THI calculation, thermal comfort classification, and data transmission. Firebase is used as the cloud-based data storage platform, while the web dashboard provides remote visualization of the measurement results.

Firebase Realtime Database is a NoSQL cloud database service that enables data storage and synchronization between connected devices and applications [16]. The database structure contains the following parameters: id as a unique data identifier, waktu as the measurement timestamp, tt_air as air temperature, rh as relative humidity, thi as the calculated THI, and status as the corresponding thermal comfort classification.

2.4. Sensor Calibration

Sensor calibration was conducted at the BMKG Central Calibration Laboratory by comparing DHT22 measurements with reference instruments. Temperature calibration was performed at set points of 20°C, 30°C, and 40°C using a Climatic Kambic Chamber and a Fluke Hart Scientific 5627A reference thermometer. Relative humidity calibration was conducted at 40%, 60%, and 80% using a Rotronic HG2S chamber and a Vaisala HMT 333 reference instrument. The calibration procedure was used to determine the measurement error and correction parameters of the DHT22 sensor [17].

The correction value was calculated as the difference between the reference measurement and the sensor reading:

$$C = X_{\text{standard}} - X_{\text{sensor}} \quad (1)$$

Where X_{standard} is the reference value and X_{sensor} is the uncorrected sensor reading. The correction parameter was subsequently applied to the corresponding sensor measurement:

$$X_{\text{corrected}} = X_{\text{sensor}} + C \quad (2)$$

Thus, the temperature and relative humidity values used for THI calculation and field analysis represent corrected measurements rather than raw DHT22 outputs.

2.5. Temperature Humidity Index

The Temperature Humidity Index (THI) is an indicator to assess thermal comfort levels based on environmental conditions by combining the effects of air temperature and relative humidity into a single index, without directly considering human physiological factors [15]. First proposed by Thom (1959), the THI was subsequently modified by Nieuwolt (1977) and Emmanuel (2005) for application in tropical regions by replacing the wet-bulb temperature parameter with relative humidity, as the latter more easily obtained from standard meteorological observations [18]. In this study, THI was calculated using the following modified empirical equation [19]:

$$THI = 0.8 \times T + \left(\frac{RH \times T}{500} \right) \quad (3)$$

Where T represents ambient air temperature in degrees Celsius (°C), RH represents relative humidity in percent (%), and THI is the resulting index value. The THI classification used in this study follows Wati and Fatkhuroyan (2017) [20], as presented in Table 1.

Table 1. Thermal Comfort Classification

THI Range	Classification	Thermal Perception
THI < 21	Cold	Cool / Cold condition
21 ≤ THI < 25	Comfortable	Optimal human thermal comfort
25 ≤ THI ≤ 27	Partly Comfortable	Mild thermal discomfort
> 27	Uncomfortable	High thermal discomfort / Heat stress

2.6. Urban–Rural Thermal Comparison

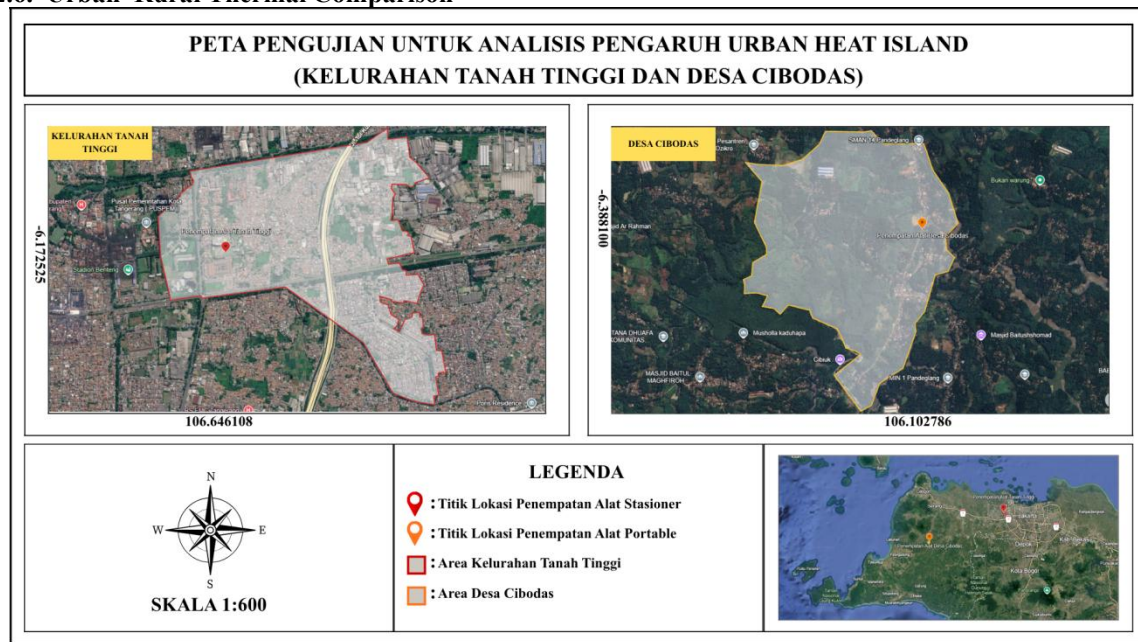


Fig. 4. Map of monitoring locations in Tangerang (Urban) and Serang (Rural)

To assess urban–rural thermal differences, two monitoring units were deployed simultaneously at two locations with contrasting urban characteristics. The urban site was located in Kelurahan Tanah Tinggi (-6.172525 , 106.646108 ; elevation 12.53 m above sea level), while the rural comparison site was located in Desa Cibodas (-6.388100 , 106.102786 ; elevation 99.63 m above sea level). Site classification was based on the Regulation of the Head of Statistics Indonesia (BPS) No. 120 of 2020 concerning the Classification of Urban and Rural Areas in Indonesia [21].

Field measurements were conducted continuously for 24 hours, from 18 July 2026 at 08:00 WIB to 19 July 2026 at 07:59 WIB. Both monitoring units were operated using the same measurement interval to enable temporal comparison between the two locations. Air temperature and relative humidity were measured simultaneously, and THI was calculated from the corrected sensor measurements.

The comparison was intended to characterize differences in air temperature, relative humidity, and thermal comfort between the urban and rural sites. The observed urban–rural differences were interpreted as thermal contrasts consistent with the UHI phenomenon, rather than as a definitive measurement of UHI intensity, because the observations were limited to two locations and a short monitoring period.

The two sites also differed in elevation and local environmental characteristics. The urban site was located at 12.53 m above sea level, whereas the rural site was located at 99.63 m above sea level. Therefore, differences in elevation, vegetation, land cover, shading, and other local environmental conditions may contribute to the observed thermal differences in addition to urbanization.

3. RESULTS AND DISCUSSION

3.1. Calibration Results

Calibration tests of the two DHT22 sensors were conducted at the BMKG Central Calibration Laboratory to determine their measurement errors and correction parameters. The results for temperature and relative humidity are presented in Tables 2 and 3.

Table 2. Temperature Sensor Calibration Results

Standard	DHT22-1	Correction	DHT22-2	Correction
20.241	20.200	0.041	20.300	-0.059
30.250	30.200	0.050	30.200	0.050
40.264	40.400	-0.136	40.200	0.064

As presented in Table 2, the calibration results reveal that the temperature measurement corrections for sensor DHT22-1 range between -0.136°C to 0.050°C . Meanwhile, sensor DHT22-2 exhibits narrower temperature corrections, ranging from -0.059°C to 0.064°C .

Table 3. Relative Humidity Sensor Calibration Results

Standard	DHT22-1	Correction	DHT22-2	Correction
39.95	40.00	-0.09	39.90	0.03
60.23	61.10	-0.87	60.30	-0.07
80.92	80.20	0.72	80.30	0.62

Table 3 illustrates the relative humidity calibration results. The humidity reading corrections for sensor DHT22-1 range from -0.87% to 0.72%, whereas sensor DHT22-2 demonstrates higher stability with corrections spanning from -0.07% to 0.62%. The calibration results show that the DHT22 sensors exhibited relatively small measurement deviations across the tested temperature and relative humidity ranges. The correction values were determined from the difference between the reference measurements and the corresponding sensor readings. These correction parameters were subsequently applied to the sensor measurements used during field observations.

3.2. Hardware and Software Implementation



Fig. 5. (a) Instrument at Cibodas; (b) instrument at Tanah Tinggi

The physical deployment of the monitoring instruments at the two observation sites is shown in Fig. 5. Each unit consisted of a DHT22 sensor housed in a Stevenson screen, an ESP32 DevKit V1, a MiFi router for wireless communication, a rechargeable battery pack, and a 20×4 I2C LCD. The Stevenson screen was used to reduce direct exposure of the sensor to solar radiation and precipitation, while the electronic components were placed inside a protective enclosure.

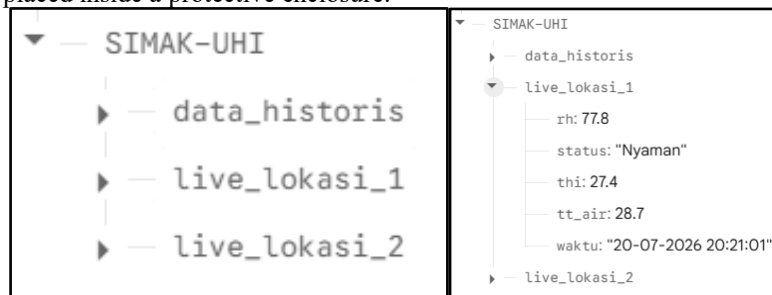


Fig. 6. Database Implementation

The Firebase Realtime Database implementation is shown in Fig. 6. Measurement data were organized under the SIMAK-UHI database into historical and site-specific nodes. The stored parameters included air temperature (tt_air), relative humidity (rh), THI (thi), thermal comfort classification (status), and measurement time (waktu). The database enabled the measurements from both monitoring units to be stored and accessed by the web application.

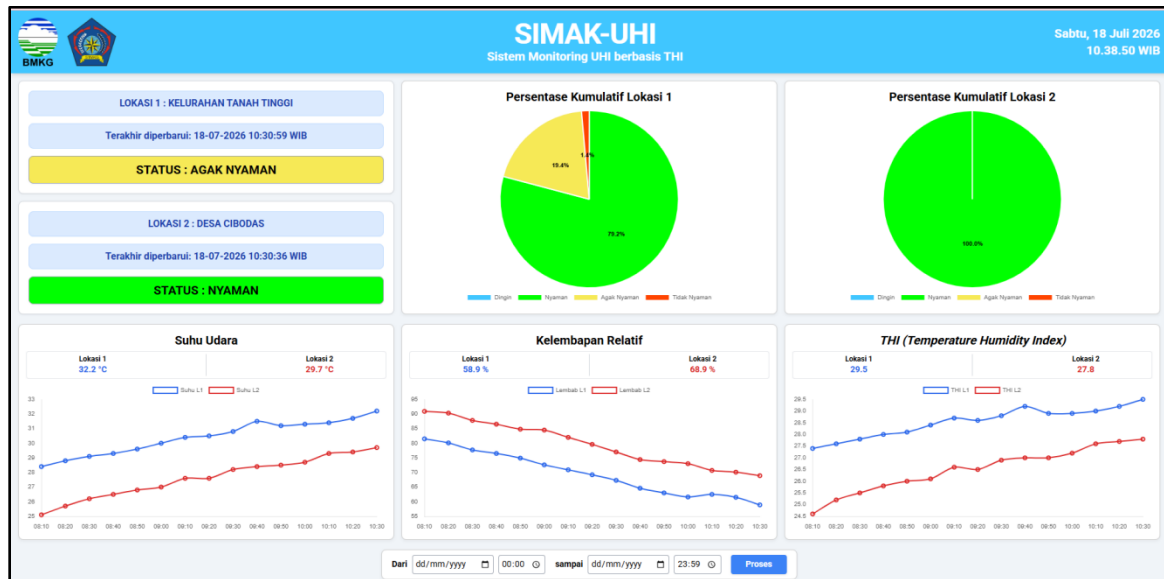


Fig. 7. Web Interface Implementation

The web interface developed for the system is presented in Fig. 7. The dashboard provides real-time visualization through time-series charts, status indicators, and historical data tables. This configuration enables remote observation of temperature, relative humidity, and THI from the two monitoring locations.

3.3. Air Temperature

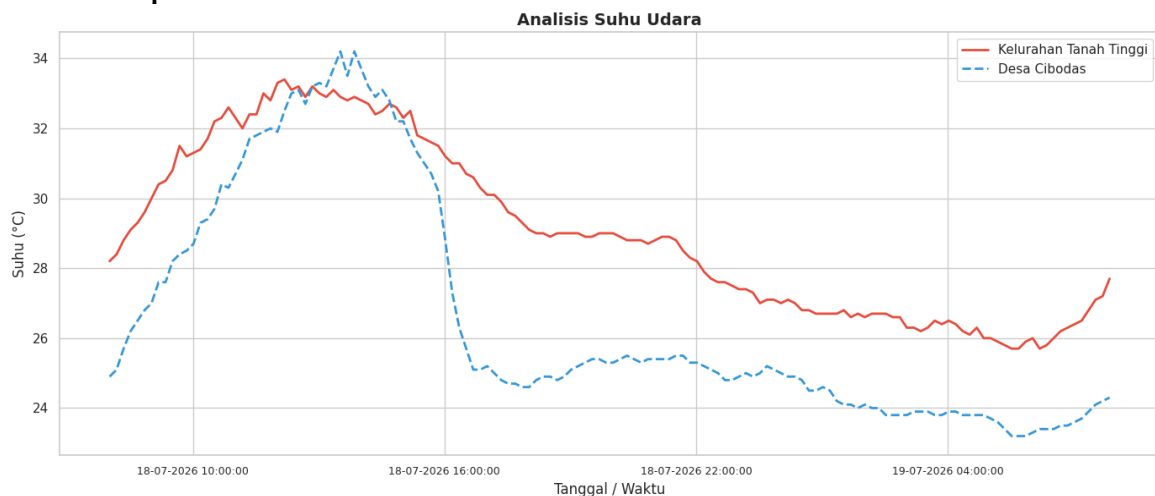


Fig. 8. Ambient Air Temperature Profile

The air temperature profiles at the two locations are shown in Fig. 8. Both sites exhibited a similar diurnal pattern, with temperature generally increasing from morning toward midday and decreasing during the afternoon and nighttime.

Kelurahan Tanah Tinggi recorded a maximum temperature of 33.4°C and a minimum of 25.7°C, while Desa Cibodas recorded a maximum of 34.2°C and a minimum of 23.2°C. The mean temperature was 29.05°C at Tanah Tinggi and 26.63°C at Cibodas, resulting in a difference of 2.42°C. Although the rural site recorded a slightly higher maximum temperature, the urban site maintained a higher minimum and mean temperature during the observation period. This pattern indicates greater persistence of warm conditions at the urban site.

The higher minimum and mean temperatures observed at Tanah Tinggi are consistent with an urban–rural thermal contrast. However, this difference may also be influenced by elevation, vegetation, land cover, shading, and other local environmental characteristics. Therefore, the observed temperature pattern should be interpreted as consistent with the UHI phenomenon rather than as definitive evidence of UHI intensity.

3.4. Relative Humidity

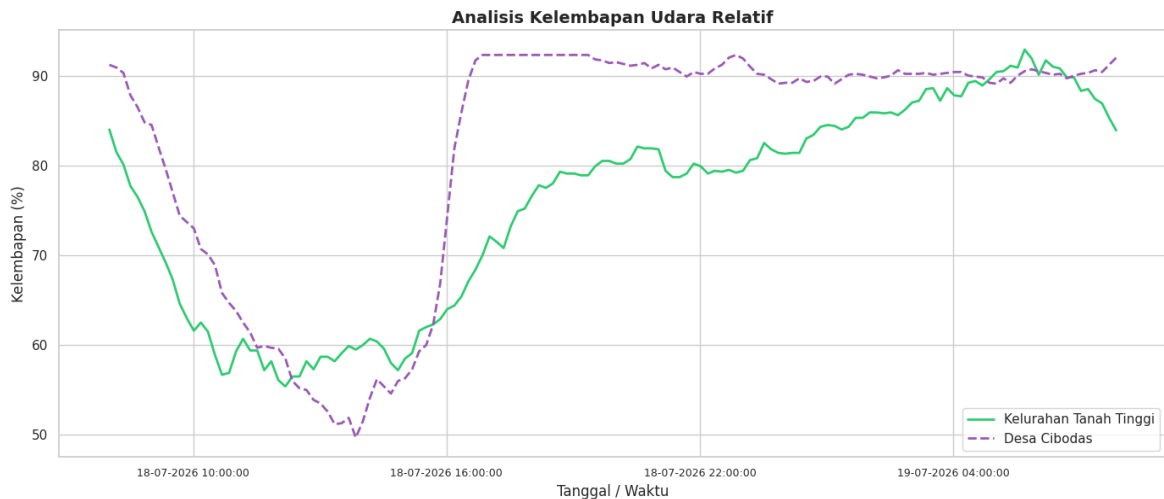


Fig. 9. Relative Humidity Profile

The relative humidity profiles are presented in Fig. 9. Both locations generally exhibited higher relative humidity during nighttime and early morning and lower values during periods of higher temperature. The maximum relative humidity was 92.9% at Tanah Tinggi and 92.3% at Cibodas, while the minimum values were 55.4% and 49.7%, respectively. The mean relative humidity at Tanah Tinggi was 75.77%, compared with 81.93% at Cibodas, representing a difference of 6.16 percentage points.

The lower mean relative humidity at the urban site occurred alongside its higher mean air temperature. Differences in vegetation, land cover, moisture availability, and local atmospheric conditions may contribute to the observed humidity contrast. Therefore, the difference should be considered as a site-specific microclimatic contrast rather than being attributed solely to urbanization.

3.5. Temperature Humidity Index

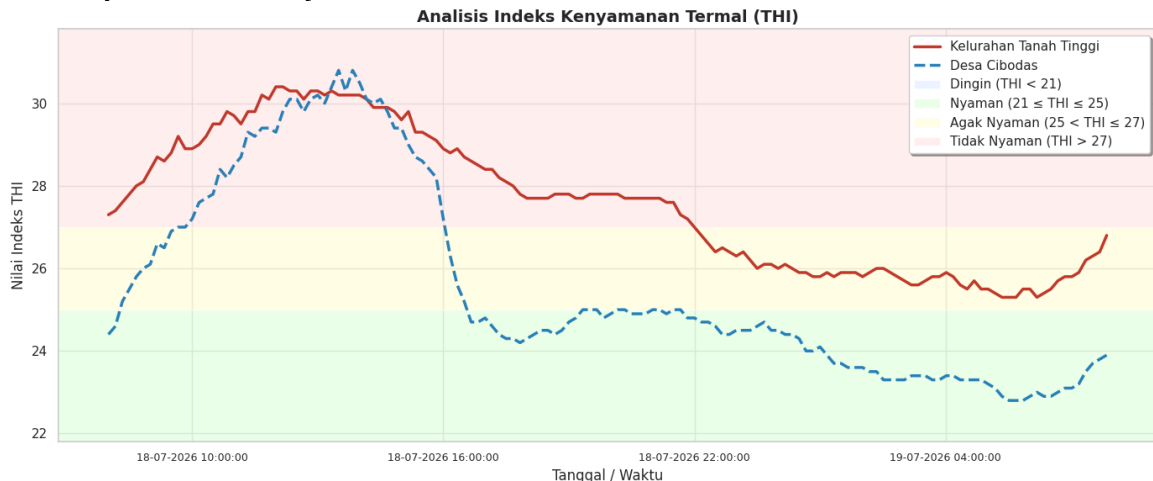


Fig. 10. Temperature Humidity Index (THI) Profile

The THI profiles for the two monitoring locations are presented in Fig. 10. The THI generally followed the temporal variation of air temperature, with higher values observed during warmer periods and lower values during nighttime and early morning. During the 24-hour observation period, the maximum THI values were 30.4 at Kelurahan Tanah Tinggi and 30.8 at Desa Cibodas, while the minimum values were 25.3 and 22.8, respectively. The mean THI was 27.59 at Tanah Tinggi and 25.57 at Cibodas, resulting in a mean difference of 2.02.

Based on the THI classification adopted from Wati and Fatkhuroyan (2017), the mean THI at Tanah Tinggi (27.59) was categorized as “Uncomfortable”, whereas the mean THI at Cibodas (25.57) was categorized as “Partly Comfortable.” The higher mean THI at Tanah Tinggi indicates warmer thermal conditions during the observation period compared with Cibodas. The difference in THI is associated with variations in air

temperature and relative humidity between the two locations. However, the observed thermal difference may also be influenced by differences in elevation, vegetation, land cover, and other local environmental characteristics.

3.6. Cumulative THI Distribution

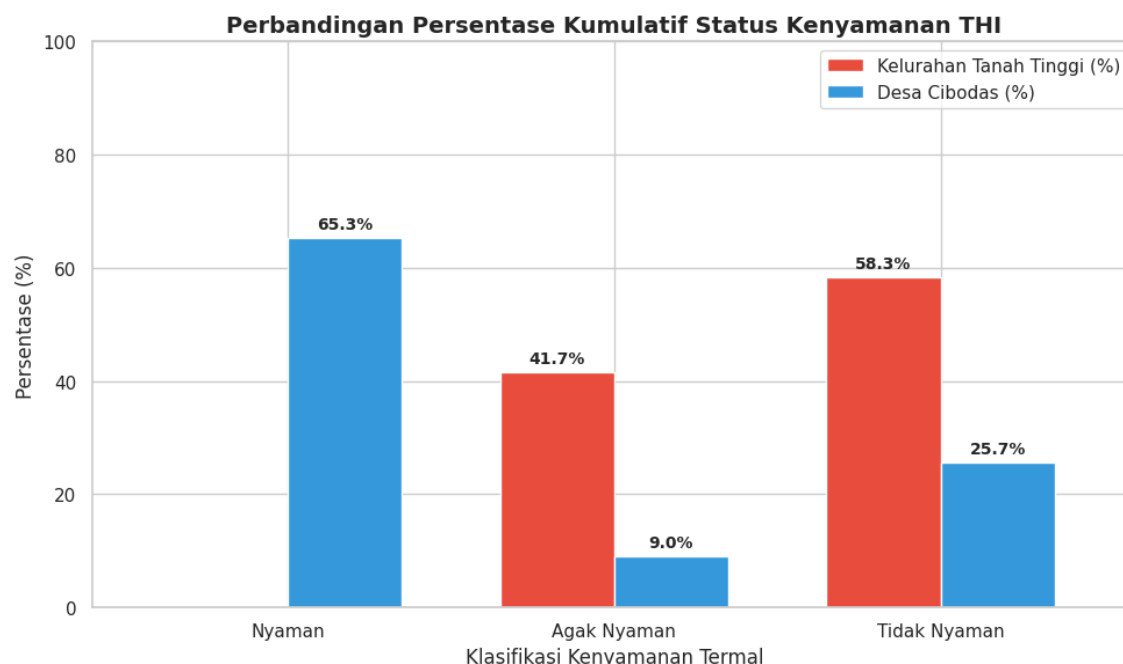


Fig. 11. Cumulative THI Percentage

The cumulative distribution of THI classifications is presented in Fig. 11. At Kelurahan Tanah Tinggi, 58.33% of the observations were classified as “Uncomfortable”, while 41.67% were classified as “Partly Comfortable.” No observations were classified as “Comfortable” during the monitoring period. At Desa Cibodas, 65.28% of the observations were classified as “Comfortable,” followed by 25.69% classified as “Uncomfortable” and 9.03% classified as “Partly Comfortable.” The “Cold” category was not observed at either location.

The distribution indicates that Tanah Tinggi experienced a greater proportion of thermally uncomfortable conditions than Cibodas during the 24-hour observation period. In contrast, Cibodas was predominantly within the “Comfortable” category. This difference is consistent with the higher mean air temperature and THI observed at Tanah Tinggi. Previous studies have reported that vegetation and natural land cover can contribute to the moderation of local thermal conditions [7]–[10]. Nevertheless, these factors were not independently measured in the present study, and therefore their specific contribution cannot be quantified.

Overall, the results demonstrate an urban–rural thermal contrast during the 24-hour monitoring period, with Tanah Tinggi exhibiting a higher mean air temperature and THI and a greater proportion of “Uncomfortable” conditions than Cibodas. This pattern is consistent with an urban heat island pattern; however, it should not be interpreted as a definitive quantification of UHI intensity because the comparison was based on only two monitoring locations with different elevations and local environmental characteristics. Longer observation periods and additional monitoring locations with comparable environmental conditions are required to better distinguish the influence of urbanization from other topographic and microclimatic factors.

3.7. Limitations

This study has several limitations that should be considered when interpreting the observed urban–rural thermal differences. First, the comparison was conducted at only two single-point monitoring sites over a limited 24-hour observation period. The monitored sites also differ in elevation and local environmental characteristics. Cibodas is located at 99.63 m above sea level (ASL), whereas Tanah Tinggi is located at 12.53 m ASL. Based on a standard environmental lapse rate of approximately 0.65°C per 100 m, the 87.10 m elevation difference could account for approximately 0.57°C of the observed 2.42°C difference in mean air temperature. Therefore, the observed temperature contrast cannot be attributed solely to urbanization, as topography, land cover, and vegetation may also influence the local microclimate.

Second, the 24-hour observation period provides only a short-term representation of the thermal conditions and does not capture diurnal patterns over multiple days, seasonal variability, or long-term UHI behavior. Third, the use of only two monitoring locations limits the spatial representativeness of the results. Consequently, the observed urban–rural thermal contrast should be interpreted as consistent with an urban heat island pattern rather than as a definitive quantification of UHI intensity. Future studies should employ longer observation periods and multiple monitoring sites with comparable elevation and systematically characterized environmental conditions to better isolate and quantify the contribution of urbanization to thermal differences.

4. CONCLUSION

This study designed, calibrated, and deployed a low-cost IoT-based instrumentation system for real-time microclimate monitoring and outdoor thermal comfort assessment using the Temperature-Humidity Index (THI). The system integrates a DHT22 sensor, ESP32 microcontroller, LCD, Firebase Realtime Database, and web dashboard to support local and remote monitoring. Laboratory calibration was conducted against BMKG reference instruments to determine sensor measurement deviations and correction parameters for air temperature and relative humidity. The corrected measurements were subsequently used for THI calculation and field observations.

During the 24-hour urban–rural comparison, with measurements recorded at 10-minute intervals, Tanah Tinggi recorded a higher mean air temperature (29.05°C) than Cibodas (26.63°C), with a difference of 2.42°C. Mean relative humidity was 75.77% at Tanah Tinggi and 81.93% at Cibodas, while mean THI values were 27.59 and 25.57, respectively. Based on the THI classification adopted from Wati and Fatkhuroyan (2017), the mean THI at Tanah Tinggi was categorized as “Uncomfortable,” whereas Cibodas was categorized as “Partly Comfortable.” The cumulative THI distribution showed that 58.33% of observations at Tanah Tinggi were classified as “Uncomfortable” and 41.67% as “Partly Comfortable.” At Cibodas, 65.28% were classified as “Comfortable,” 25.69% as “Uncomfortable,” and 9.03% as “Partly Comfortable.”

These results indicate an urban–rural thermal contrast consistent with an urban heat island pattern. However, the findings should not be interpreted as a definitive quantification of UHI intensity because the observation was limited to two sites over 24 hours, and the sites differed in elevation and local environmental characteristics. Future research should involve longer monitoring periods and multiple monitoring locations with comparable environmental conditions to improve the spatial and temporal representation of urban–rural thermal conditions and better isolate the influence of urbanization.

DECLARATIONS

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- **Author Contributions:** Muhammad Afif: Conceptualization, Methodology, Software, Data Acquisition, Investigation, and Writing – Original Draft. Dibyo Susanto, Muchamad Rizqy Nugraha, and Achmad Fahrudin Rais: Supervision, Validation, Review, and Editing.
- **Conflict of Interest:** The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.
- **Data Availability:** The raw telemetry records generated during the field deployment are stored in the Firebase Realtime Database. The calibration datasets and analytical data used in this study are available from the corresponding author upon reasonable request, subject to applicable institutional restrictions.
- **Generative AI Use:** Generative AI tools (Google Gemini) were used solely for English-language grammar correction and translation refinement of author-generated text. All conceptualization, experimental design, data acquisition, calculations, data analysis, and interpretation were performed by the authors.
- **Ethics Approval and Informed Consent:** Not applicable.

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