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Spatio-Temporal Analysis of Thermal Comfort in High-Density Residential Areas in the Urban Region of Unaaha

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ABSTRACT

Thermal comfort plays a vital role in the health, productivity, and well-being of urban communities and serves as a critical indicator in sustainable urban planning. This study aims to analyze thermal comfort levels in dense residential areas and planned residential zones within the Unaaha urban area, using satellite data from two specific years, 2014 and 2024, selected to capture a decade of urban change. The methodology employs Landsat 8 OLI/TIRS imagery complemented by shapefile data of planned residential areas in Unaaha District, providing spatial context for detailed analysis. The spatial resolution and quality of the satellite imagery ensure reliable detection of land surface temperature and vegetation changes. A series of index transformations, including Urban Index (UI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Land Surface Temperature (LST), Modified Temperature Humidity Index (MTHI), and Thermal Index (TI), were applied to assess thermal comfort dynamics. Results indicate significant changes in thermal comfort between 2014 and 2024, with a shift in dominant categories from "uncomfortable" (60.5%) in 2014 to "less comfortable" (67.71%) in 2024 within dense residential areas. Evaluation of the 2024 planned residential zones reveals a predominance of "less comfortable" (45.34%) and "uncomfortable" (27.81%) classes. These findings suggest that current residential planning has not adequately balanced green open spaces and built-up areas, thereby limiting the natural cooling effects. This outcome aligns with previous studies emphasizing the critical role of green infrastructure in mitigating urban heat, underscoring the need for integrative planning approaches that prioritize thermal comfort in urban development.

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Introduction

Rapid urbanization and global climate change pose significant challenges to thermal comfort in high-density urban residential areas. One prominent effect of these changes is the intensification of the Urban Heat Island (UHI) phenomenon, which recent studies indicate can increase temperatures in tropical cities by 5–8°C above those in surrounding rural areas (Santamouris et al., 2022). However, it is important to recognize that UHI intensity varies considerably across tropical urban environments owing to factors such as city morphology, vegetation cover, and socioeconomic conditions, highlighting the need for localized studies to capture this variability accurately.

This rise in urban temperatures is strongly correlated with increased health risks, including cardiovascular diseases and heat stress, particularly among vulnerable populations, such as the elderly and children (WHO, 2023). The physiological impacts of thermal discomfort arise from disruptions in the body's thermoregulation mechanisms, which can exacerbate pre-existing health conditions and lead to severe health consequences. Thus, understanding these mechanisms is critical for developing effective public health and urban-planning responses.

As a developing country with a tropical climate, Indonesia faces unique challenges in adapting to climate change. The country's climate is characterized by two primary seasons and complex monsoon patterns, resulting in high variability (Aldrian et al., 2021). With annual rainfall ranging between 2,000 and 3,000 mm across most regions, Indonesia contends with the dual threats of flooding and drought, both of which can significantly influence thermal comfort in residential areas. These climatic patterns have become increasingly unpredictable owing to global climate change, intensifying the urgency for adaptive strategies (Ratri et al., 2022).

Wijaya et al. (2023) reported that Indonesian cities have experienced an average temperature increase of 0.3°C per decade over the last 30 years, with higher warming trends observed in areas with high building density. This empirical evidence explicitly links temperature increases to the intensification of urban heat islands and the consequent deterioration of the thermal comfort. This situation is exacerbated by extensive land-use transformations, where vegetated areas are converted into built-up zones without adequate consideration of long-term thermal impacts (Sari & Anorogo, 2018).

The Unaaha District, located in Southeast Sulawesi, exemplifies significant spatiotemporal dynamics. Unaaha, with a population of 26,027 and a density of 276 inhabitants per km² (BPS, 2023), faces challenges related to thermal comfort arising from changes in land use patterns and increasing building density. Population growth and density intensify urban microclimatic effects by reducing vegetation cover and increasing heat retention through impervious surfaces, aggravating thermal discomfort.

The area is characterized by good accessibility coupled with rapid spatial transformation, making it a strategic site for examining spatiotemporal dynamics of thermal comfort. Previous research on urban thermal comfort has predominantly focused on large metropolitan areas (Pratiwi et al., 2024; Zhao & Li, 2023). However, these studies have not fully explored the temporal dynamics of thermal comfort in small-to medium-sized cities experiencing rapid urbanization, such as Unaaha. Addressing this gap is essential, given that urbanization patterns in smaller cities have distinct characteristics and challenges compared to larger urban centers (Hernandez & Tiangco, 2022). For instance, smaller cities often undergo more heterogeneous land use changes and face different socio-economic constraints that influence thermal environments and residents' adaptive capacity.

Spatiotemporal analytical methods employing multi-temporal and multi-sensor approaches can provide a more comprehensive understanding of thermal comfort dynamics in high-density residential areas (Rahman et al., 2023). This approach enables the identification of land surface temperature (LST) change patterns and their relationships with land cover changes, building density, and vegetation indices.

Methodology

Study Area

This study was conducted in the Unaaha District, which is geographically situated between latitudes 3°48′0″ and 3°53′32″ South and longitudes 122°1′40″ and 122°5′13″ East. Unaaha, covering an area of approximately 2,715.57 hectares, serves as the administrative capital of Konawe Regency in Southeast Sulawesi, Indonesia. The district has experienced rapid urbanization and continuous population growth, making it an ideal setting for analyzing spatiotemporal thermal comfort dynamics. Administratively, Unaaha is bordered by the Tongauna and Anggaberi Districts to the north, Anggaberi, Wawotobi, and Konawe Districts to the east, Uepai and Tongauna Districts to the west, and Uepai District to the south. The district’s diverse land-use patterns and spatial transformations provide a robust framework for examining the interaction between urban development and thermal conditions.

Research Tools and Materials

The analytical framework employed ArcMap 10.8 GIS software for spatial data processing and analysis, supplemented by a high-performance laptop for computational tasks and a smartphone for ground-truthing and field data verification. The remote sensing datasets consisted of Landsat 8 OLI/TIRS imagery acquired in 2014 and Landsat 9 imagery from 2024, selected to capture a decadal interval reflective of urban growth and climatic variation. Both datasets were obtained during the dry season to minimize atmospheric variability caused by cloud cover and precipitation. Complementary shapefile data delineating Unaaha District administrative boundaries and residential planning zones (RDTR) were incorporated to spatially contextualize the analysis results within land-use frameworks.

Research Variables

This study focuses on the key biophysical variables influencing thermal comfort: surface temperature and moisture content. The surface temperature was quantified using Land Surface Temperature (LST) derived from satellite thermal bands, serving as a proxy for urban heat conditions. Moisture levels were assessed using the Normalized Difference Moisture Index (NDMI), which quantifies the vegetation and soil moisture status. To integrate these variables into a comprehensive thermal comfort indicator, the modified temperature-humidity index (MTHI) was computed, incorporating both temperature and moisture data to better reflect human thermal perception in urban environments.

Data Preprocessing

To ensure accuracy and consistency, the preprocessing of Landsat 8 and 9 OLI/TIRS images included radiometric and atmospheric corrections. Radiometric correction was performed to correct for sensor errors and atmospheric disturbances that distorted reflectance values. Following the USGS (2014) protocol, the top-of-atmosphere (ToA) reflectance ($\rho\lambda'$) was calculated for each spectral band using the following formula:

$$\rho\lambda' = M_{\rho} \times Q_{cal} + A_{\rho}$$

Where:

$\rho\lambda'$ = ToA reflectance without solar angle correction
$M\rho$ = Reflectance multiplicative scaling factor for band x
$A\rho$ = Reflectance additive scaling factor for band x
Q_{cal} = Digital Number (DN) value

Solar angle correction was then applied to remove the differences in DN values caused by the solar position, which varies with the time and location of image acquisition. The correction was performed using

$$\rho\lambda = \frac{\rho\lambda'}{\cos(\theta_{sz})}$$

Where:
ρλ = Solar angle corrected ToA reflectance
θSE = Sun elevation angle
θSZ = Solar zenith angle (90∘−θSE)

Data Analysis

The Urban Index (UI) is an effective transformation model used to differentiate built-up areas from natural areas. It typically employs shortwave infrared (SWIR), near-infrared (NIR), and other spectral bands sensitive to differences between artificial materials and natural elements such as water, vegetation, and bare soil (Danoedoro, 2012). The UI is calculated as follows:

$$UI = \frac{SWIR_{II} - NIR}{SWIR_{II} + NIR}$$

Where:
SWIR II = Band 7
NIR = Band 5

This stage involved extracting the Earth's surface temperature at the time of satellite image acquisition. After radiometric correction, the satellite brightness temperature (TB) was converted from radians to Kelvin and then to Celsius. Vegetation indices (NDVI) were calculated to derive the proportion of vegetation (PV) and surface emissivity values. NDVI is computed as:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Where:
NIR = Band 5
Red = Band 4
The proportion of vegetation (PV) was calculated as follows:

$$PV = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2$$

The surface emissivity (ε) is then estimated as

$$\epsilon = 0.004 \times PV + 0.986$$

Finally, the LST was computed using the following equation:

$$LST = \frac{TB}{1 + \left(\frac{\lambda \times \mathrm{TB}}{\rho}\right) In\ \varepsilon}$$

Satellite brightness temperature (°C)
Wavelength of emitted radiance
p=shc=1.4388×10−2m·K=14.388μm·K
According to Haikal (2014), NDMI is defined as the following:

$$NDMI = \frac{NIR - SWIR}{NIR + SWIR}$$

Where:
NIR = Near Infrared reflectance
SWIR = Shortwave Infrared reflectance

The modified temperature-humidity index, which represents a humidity-related thermal comfort measure, is calculated as follows:

$$MTHI = 1.8 \times LST + 32 - 0.55 \times (1 - NDMI) \times (1.8 \times LST - 26)$$

The Thermal Index uses the standard deviation to measure the dispersion of MTHI values relative to their mean, providing insight into thermal comfort variability. TI is computed as:

$$TI = \frac{MTHI - \overline{MTHI}}{\sigma MTHI}$$

This index reflects the relative thermal comfort of a specific location compared with that of the entire study area.

Table 1. Thermal Comfort Levels Based on Thermal Index Range during the Summer Season

Class	*Thermal Index (TI) Range*	*Description*
1	*TI ≤ 1,5α*	*Very Comfortable*
2	*-1,5α < TI ≤ -0,5α*	*Comfortable*
3	*-0,5α < TI ≤ 0,5α*	*Less Comfortable*
4	*0,5 α < TI ≤ 1,5α*	*Uncomfortable*
5	*1,5α < TI*	*Very Uncomfortable*

Source: Feng et al., 2020

Result and Discussion

Topography

The Unaaha District is predominantly characterized by alluvial plains formed through the deposition of sediments transported by the Konaweeha River and its tributaries. These plains exhibit relatively flat to gently sloping terrain, with slopes ranging from 0 to 8%. The alluvial deposits consist mainly of sand, silt, and gravel, which have undergone sorting and transportation by fluvial processes. Such sediment composition and terrain morphology contribute to favorable conditions for urban development and residential expansion. However, the extensive conversion of these permeable surfaces into built-up areas can lead to reduced infiltration capacity and altered surface thermal properties, potentially exacerbating the urban heat island effect.

Rainfall

For this study, Landsat 8 imagery captured on November 11, 2014, and Landsat 9 imagery acquired on April 26, 2024, were used, both corresponding to the dry season in Unaaha to minimize atmospheric disturbances such as cloud cover and precipitation effects. In 2014, meteorological records indicated that Unaaha experienced 123 rainy days with a total rainfall of 1,760.8 mm and an average wind speed of 1.68 m/s, sourced from BP3K Unaaha (2014) and Maritime Meteorological Station Kendari (2014). June 2014 recorded the highest frequency of rainy days (22 days) and greatest rainfall intensity (136.60 mm). A peak wind speed of 0.96 m/s was observed in December 2014. These climatic parameters influence surface moisture and temperature regimes, impacting thermal comfort indices derived from satellite data.

In 2024, the district experienced 120 rainy days with a lower total rainfall of 1,150.5 mm and an increased average wind speed of 9.85 m/s, as reported by the BMKG UPT Climatology Station South Konawe (2024) and Maritime Meteorological Station Kendari (2024). Table 2 summarizes the monthly rainfall, rainy days, and wind speed data for both years. The decrease in rainfall and increase in wind speed in 2024 may affect land surface temperature and moisture distribution, necessitating consideration when interpreting thermal comfort changes.

Table 2. Rainfall in Unaaha District

Month	*2014: Rainy Days*	*Rainfall (mm)*	*Wind Speed (m/s)*	*2024: Rainy Days*	*Rainfall (mm)*	*Wind Speed (m/s)*
January	*6*	*100.80*	*0.06*	*8*	*95.00*	*0.8*

February	*16*	*193.40*	*0.00*	*9*	*41.50*	*0.89*
March	*11*	*251.60*	*0.00*	*16*	*172.00*	*0.9*
April	*13*	*181.40*	*0.00*	*11*	*121.00*	*0.6*
May	*15*	*288.60*	*0.00*	*14*	*124.00*	*0.64*
June	*22*	*367.80*	*0.00*	*18*	*198.50*	*0.73*
July	*8*	*136.60*	*0.00*	*10*	*77.50*	*0.8*
August	*11*	*98.30*	*0.00*	*5*	*25.00*	*0.93*
September	*0*	*0.00*	*0.00*	*3*	*22.50*	*0.96*
October	*0*	*0.00*	*0.00*	*0*	*0.00*	*0.9*
November	*4*	*70.10*	*0.66*	*10*	*71.00*	*0.96*
December	*17*	*142.30*	*0.96*	*16*	*202.50*	*0.74*
Total	*123*	*1,760.80*	*1.68*	*120*	*1,150.50*	*9.85*

Source: BP3K Unaaha, 2014; Maritime Meteorological Station Kendari, 2014; BMKG UPT Climatology Station South Konawe, 2024; Maritime Meteorological Station Kendari, 2024

Population

Population data sourced from the Central Bureau of Statistics (BPS) indicate that Unaaha's population increased modestly from 24,480 individuals in 2014 to 24,776 in 2024, reflecting a growth rate of approximately 0.12% per year. The spatial distribution of the population reveals that Ambekairi Subdistrict had the highest population (3,314 residents) in 2014, while Latoma Subdistrict had the lowest (1,115 residents). By 2024, the Tumpas Subdistrict recorded the highest population (3,579 residents), with the Tobeu Subdistrict having the lowest (776 residents). These variations in population density influence urban land use and surface thermal properties, with denser areas generally exhibiting higher built-up surface ratios and greater risks of thermal discomfort.

Cloud Masking on Imagery

Owing to the significant cloud cover in the 2024 Landsat imagery, cloud masking Owing to the significant cloud cover in the 2024 Landsat imagery, cloud masking procedures were applied to ensure the quality and accuracy of the satellite-derived thermal data. The cloud masking process was employed to identify and exclude cloud-affected pixels, resulting in a reduction of the effective study area from 2,715.57 to 2,545.92 hectares. While this reduction is necessary for data integrity, it may introduce spatial bias by excluding certain land cover types, which should be considered when interpreting the spatial patterns of thermal comfort. Figure 1 illustrates the Landsat image before and after cloud masking, visually demonstrating the extent of cloud coverage and the subsequent area used for analysis.

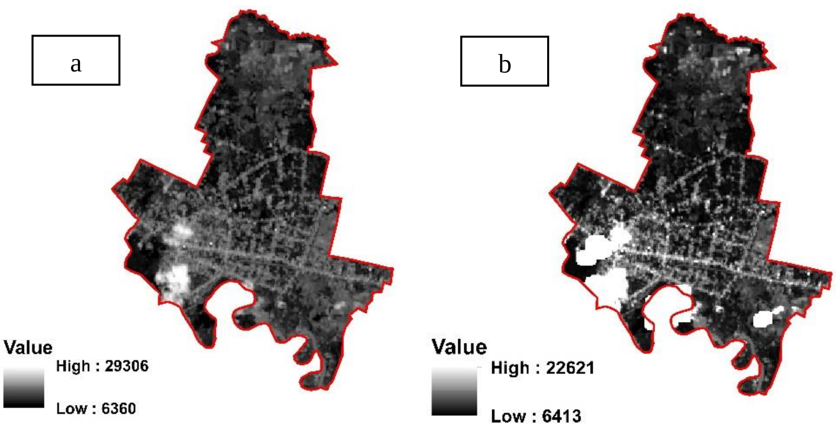


Figure 1. (a) Landsat image before cloud masking, (b) Landsat image after cloud masking

Radiometric Correction

Prior to radiometric correction, Landsat images appeared brighter owing to atmospheric effects such as Rayleigh and Mie scattering, which disproportionately increase brightness in shorter wavelengths, particularly in the blue and green bands. These scattering effects distort the surface reflectance and necessitate correction for accurate spectral analysis. Following correction, the images appeared darker as atmospheric influences were removed, providing a more realistic representation of the surface conditions. Radiometric correction was performed using established atmospheric correction models, adjusting the reflectance values to eliminate extraneous effects, such as solar angle variations and atmospheric constituents present at the time of image acquisition (USGS, 2014).

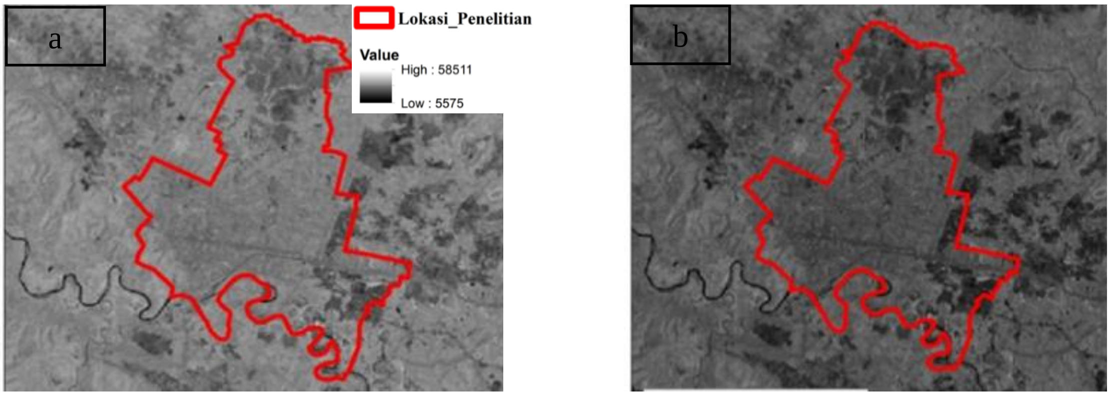


Figure 2. (a) Landsat image before radiometric correction, (b) Landsat image after radiometric correction

Thermal Comfort Results in Unaaha District

Thermal comfort in the Unaaha District for 2014 and 2024 was classified into five categories based on the Thermal Index (TI) (Figure 3). The categories ranged from “very comfortable” (dark green) to “very uncomfortable” (red), facilitating an intuitive spatial interpretation. Owing to the cloud masking applied to the 2024 imagery to ensure data quality, the effective analyzed area decreased from 2,715.57 ha to 2,545.92 ha, which introduces some spatial bias that should be considered when comparing temporal results. The TI values for 2014 ranged from -1.75368 to 2.93477 (Table 3), whereas in 2024, values ranged from -2.91138 to 2.55697 (Table 4). These ranges indicate notable shifts in the thermal conditions over the decade.

Tables 3 and 4 present the spatial distribution of the thermal comfort categories with the corresponding area coverage. Although areas classified as “very comfortable” and “comfortable” slightly increased in 2024, the dominant land cover remains in the “less comfortable” to “very uncomfortable” classes, which collectively represent a substantial portion of the district.

Table 3. Thermal Comfort Classification in Unaaha District, 2014

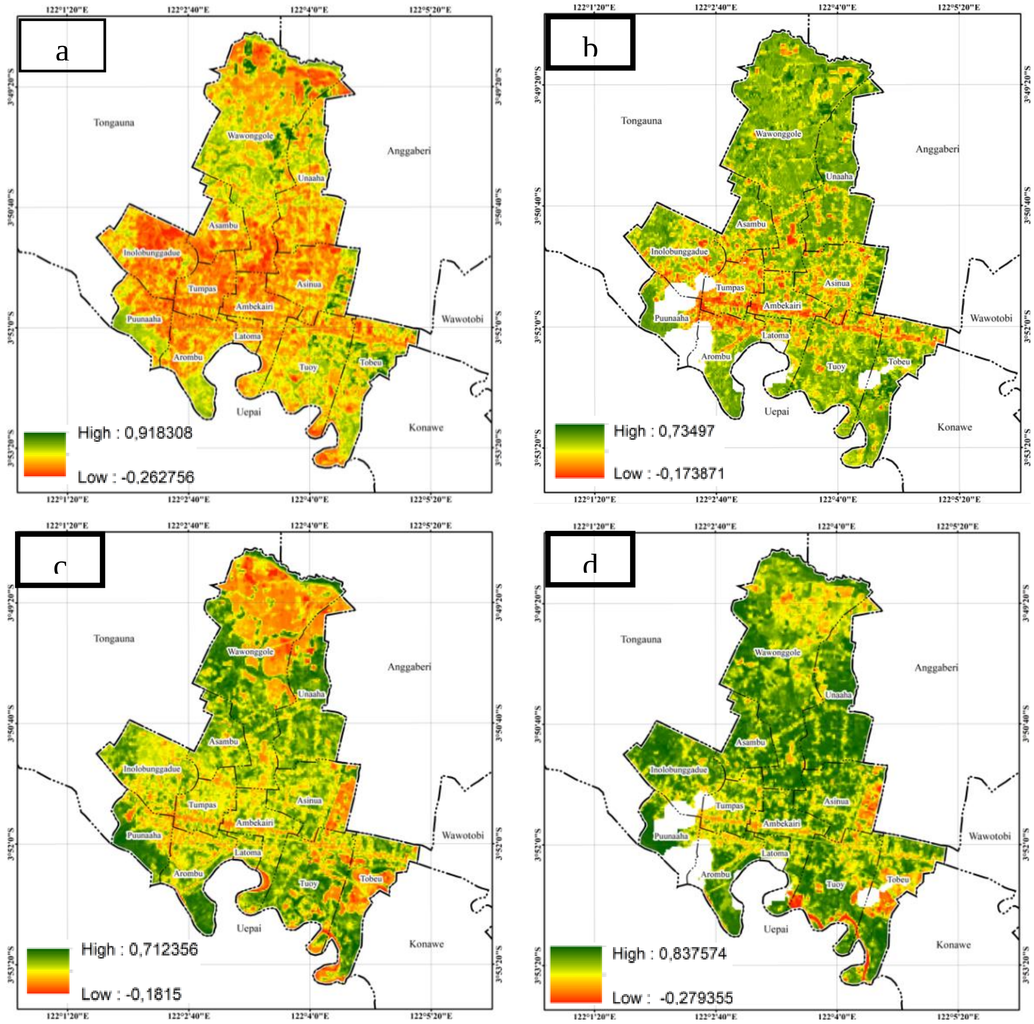
Class	*TI Range*	*Category*	*Area (ha)*
1	*TI ≤ -1,064589*	*Very Comfortable*	*530.19*
2	*-1.064589 < TI ≤ -0.354863*	*Comfortable*	*770.76*
3	*-0.354863 < TI ≤ 0,354863*	*Less Comfortable*	*656.37*
4	*0,354863 < TI ≤ 1,064589*	*Uncomfortable*	*623.61*
5	*TI > 2,934771*	*Very Uncomfortable*	*135.72*
Total			*2,716.57*

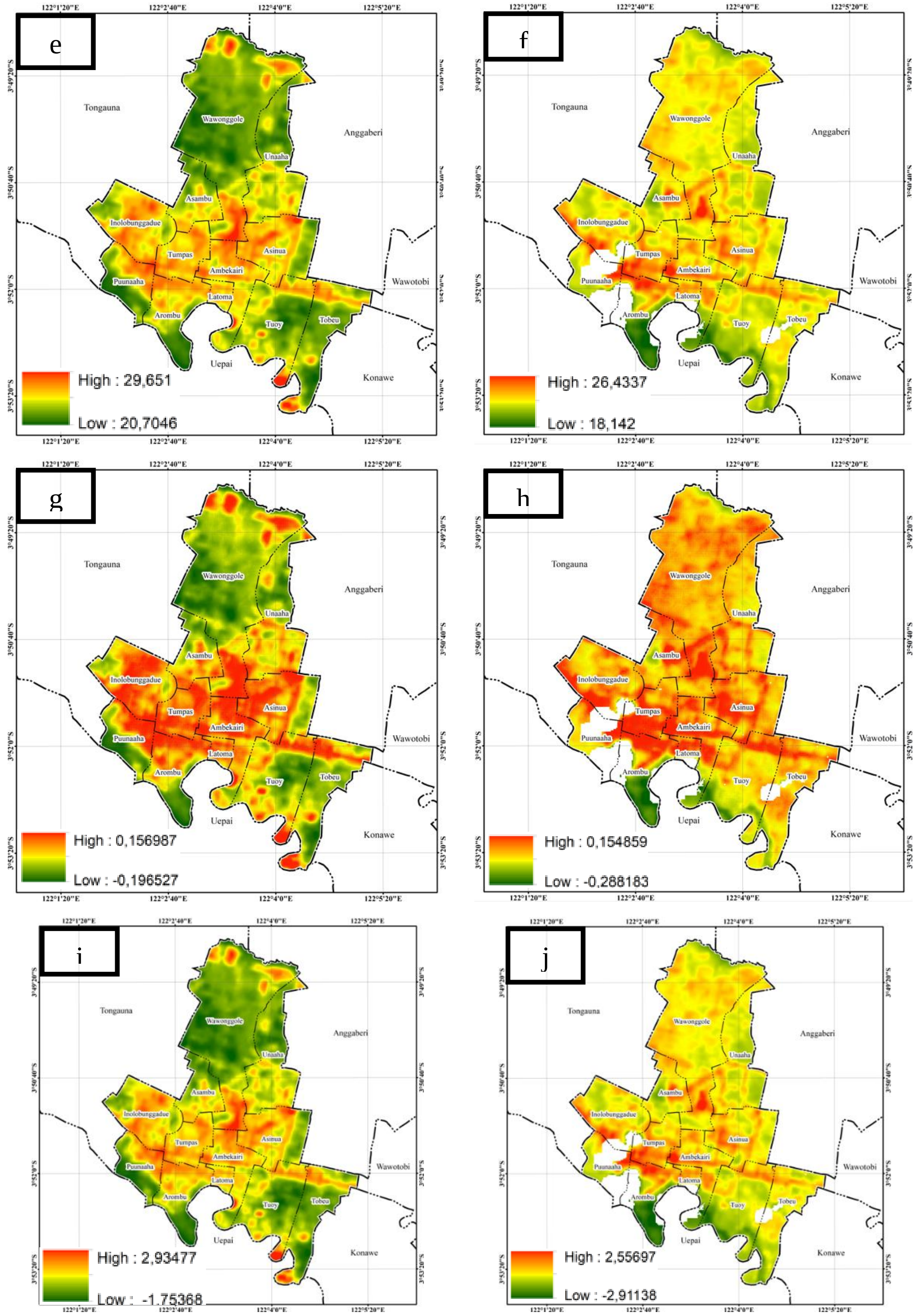
Source: Data Analysis, 2025

Table 4. Thermal Comfort Classification in Unaaha District, 2024

Class	*TI Range*	*Category*	*Area (ha)*
1	*TI ≤ -0,992814*	*Very Comfortable*	*151.02*
2	*-0,992814 < TI ≤ -0,330938*	*Comfortable*	*530.28*
3	*-0,330938 < TI ≤ 0,330938*	*Less Comfortable*	*1,183.59*
4	*0,330938 < TI ≤ 0,992814*	*Uncomfortable*	*515.16*
5	*TI > 2,5569684*	*Very Uncomfortable*	*165.87*
Total			*2,545.92*

Source: Data Analysis, 2025




e
Tongauna
Wawonggole
Anggaberi
Unaaha
Asambu
Inolobunggadue
Tumpas
Asinua
Ambekairi
Puunaaha
Latoma
Wawotobi
Arombu
Tuoy
Tobeu
Uepai
Konawe
High : 29,651
Low : 20,7046
f
High : 26,4337
Low : 18,142
g
High : 0,156987
Low : -0,196527
h
High : 0,154859
Low : -0,288183
i
High : 2,93477
Low : -1,75368
j
High : 2,55697
Low : -2,91138

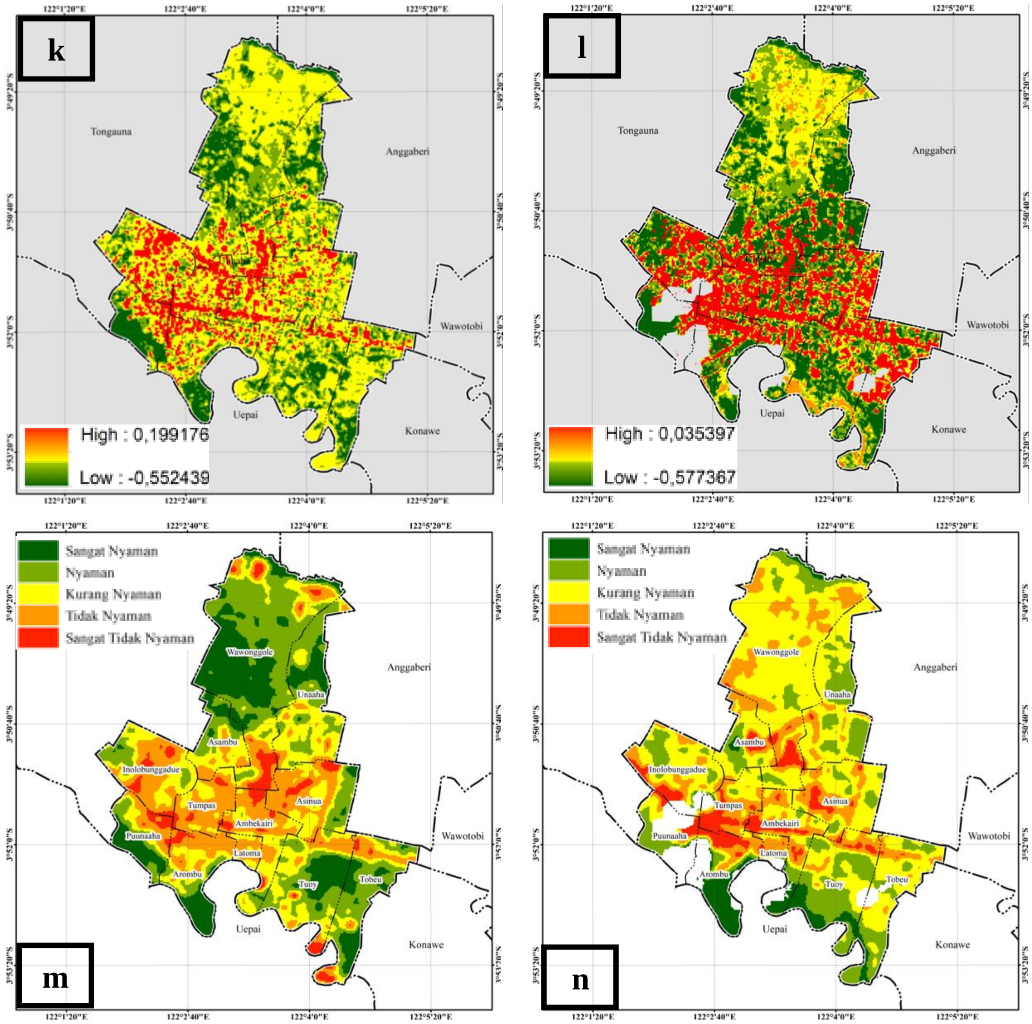


Figure 3. (a) NDMI 2014 (b) NDMI 2024 (c) NDVI 2014 (d) NDVI 2024 (e) LST 2014 (f) LST 2024 (g) MTHI 2014 (h) MTHI 2024 (i) TI 2014 (j) TI 2024 (k) UI 2014 (l) UI 2024 (m) Thermal Comfort 2014 (n) Thermal Comfort 2024

Thermal Comfort in High-Density Residential Areas of Urban Unaaha

A focused analysis of dense residential zones revealed significant changes in thermal comfort status between 2014 and 2024. In 2014, "very comfortable" areas covered a mere 0.66 hectares (0.21% of the dense residential area), and "comfortable" areas covered 4.31 ha (1.36%). In contrast, the "less comfortable," "uncomfortable," and "very uncomfortable" zones occupied 41.57 ha (13.14%), 191.74 ha (60.55%), and 78.29 ha (24.72%), respectively, summing to a majority experiencing suboptimal thermal conditions (Table 5).

Table 5. Thermal Comfort Classification in High-Density Residential Areas, Urban Unaaha, 2014

Class	*TI Range*	*Category*	*Area (ha)*
1	*TI ≤ -1,064589*	*Very Comfortable*	*0.66*
2	*-1.064589 < TI ≤ -0.354863*	*Comfortable*	*4.31*
3	*-0.354863 < TI ≤ 0,354863*	*Less Comfortable*	*41.57*
4	*0,354863 < TI ≤ 1,064589*	*Uncomfortable*	*191.74*
5	*TI > 2,934771*	*Very Uncomfortable*	*78.29*
Total			*316.57*

Source: Data Analysis, 2025

Table 6. Thermal Comfort Classification in High-Density Residential Areas, Urban Unaaha, 2024

Class	*TI Range*	*Category*	*Area (ha)*

1	*TI ≤ -0,992814*	*Very Comfortable*	*4.13*
2	*-0,992814 < TI ≤ -0,330938*	*Comfortable*	*44.50*
3	*-0,330938 < TI ≤ 0,330938*	*Less Comfortable*	*225.56*
4	*0,330938 < TI ≤ 0,992814*	*Uncomfortable*	*202.03*
5	*TI > 2,5569684*	*Very Uncomfortable*	*134.27*
Total			*610.49*

Source: Data Analysis, 2025

By 2024, the area under analysis expanded to 610.49 hectares, reflecting the urban growth. The "very comfortable" and "comfortable" areas increased to 4.13 hectares (0.68%) and 44.50 hectares (7.29%), respectively, showing a modest improvement. However, "less comfortable" zones surged dramatically to 225.56 hectares (36.96%), "uncomfortable" areas increased to 202.03 hectares (33.08%), and "very uncomfortable" areas expanded to 134.27 hectares (22.01%) (Table 6). This spatial shift demonstrates that, despite some increase in comfortable zones, the overall thermal comfort in dense residential areas has deteriorated, coinciding with urbanization-driven land use changes.

Spatial mapping (Figure 4) further illustrates that the expansion of "uncomfortable" thermal zones (marked in orange and red) is particularly prominent in the central and southern sections of Unaaha, areas experiencing intensified urban development and vegetation loss. The increase in built-up surfaces likely reduces evapotranspiration and increases heat retention, amplifying the Urban Heat Island effect.

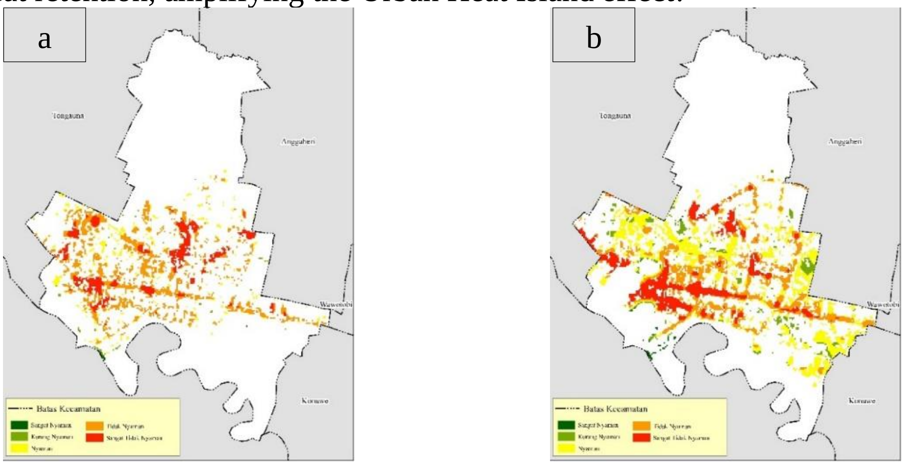


Figure 4. (a) Results of Thermal Comfort Analysis in Dense Residential Areas in Unaaha Urban Area, 2014 (b) Results of Thermal Comfort Analysis in Dense Residential Areas in Unaaha Urban Area, 2024

Thermal Comfort Results in Planned Residential Areas in Unaaha Urban Area

The analysis of planned residential zones in 2024 (Table 7, Figure 5) shows that only 2.55 hectares (0.36%) of these areas are classified as "very comfortable," predominantly due to dense vegetation and green open spaces providing natural cooling effects. An additional 114.91 hectares (16.09%) fell under the "comfortable" category, where a balance between built environments and greenery exists.

Table 7. Thermal Comfort Classification Results for 2024 in Planned Residential Areas of Unaaha Urban Area

Class	*Description*	*Interval*	*Area (ha)*
1	*Very Comfortable*	*TI ≤ -0,992814*	*2.55*
2	*Comfortable*	*-0,992814 < TI ≤ -0,330938*	*114.91*
3	*Less Comfortable*	*-0,330938 < TI ≤ 0,330938*	*323.82*
4	*Uncomfortable*	*0,330938 < TI ≤ 0,992814*	*198.76*
5	*Very Uncomfortable*	*> 2,5569684*	*74.29*

Total	*714.36*

Source: Data Analysis, 2025

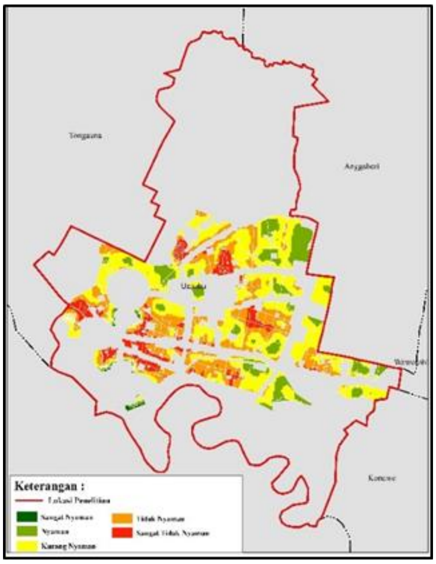


Figure 5. Thermal Comfort Results in Planned Residential Areas of Unaaha Urban Area

However, the largest share—323.82 hectares (45.34%)—is categorized as "less comfortable," reflecting extensive built-up land with diminishing vegetation cover, thereby weakening natural cooling. The "uncomfortable" (198.76 hectares, 27.81%) and "very uncomfortable" (74.29 hectares, 10.40%) classes indicate that much of the planned residential area is dominated by dense construction and minimal green infrastructure, exacerbating thermal discomfort and Urban Heat Island effects.

These findings suggest that the current allocation of green spaces within residential planning in Unaaha is insufficient to counterbalance heat accumulation. Urban planners and policymakers should prioritize the integration of larger and more strategically distributed green spaces to enhance thermal comfort and sustainability in future developments.

Conclusion

Between 2014 and 2024, significant changes in thermal comfort were observed within the dense residential areas of the Unaaha urban region, predominantly marked by a deterioration in overall comfort levels. In 2014, the combined area classified as "very comfortable" and "comfortable" was minimal, covering approximately 4.97 hectares (1.57%), while the majority of the area fell into the "less comfortable" to "very uncomfortable" categories. By 2024, although there was a modest increase in "very comfortable" (4.13 hectares; 0.67%) and "comfortable" (44.50 ha; 13.67%) zones, these gains were outweighed by a substantial rise in less favorable categories. The "less comfortable" area expanded sharply to 225.56 hectares (67.71%), the "uncomfortable" class grew to 202.03 hectares (33%), and the "very uncomfortable" category increased to 134.27 hectares (22%).

This study presents several limitations that must be acknowledged for a more accurate interpretation of its findings. One primary constraint lies in the cloud cover present in the 2024 Landsat imagery, which led to a reduction in the effective study area. This exclusion of certain regions may have introduced spatial bias, as some land cover types and thermal characteristics were omitted from the analysis. Furthermore, the research focused exclusively on biophysical indicators such as Land Surface Temperature (LST), NDVI, and NDMI, without incorporating socio-economic variables or local behavioral responses that significantly influence human thermal perception. The temporal scope was also limited, utilizing only two discrete years (2014 and 2024), which restricts the ability to observe seasonal fluctuations or long-term trends that could be critical for understanding dynamic urban thermal conditions. Additionally, the thermal comfort indices employed—MTHI and TI—were derived from remote sensing calculations without validation from field measurements or perception-based surveys, making the outcomes largely estimative. The use of index thresholds adapted from previous literature was also not recalibrated for local environmental and cultural contexts, potentially limiting their applicability to Unaaha's specific conditions. These limitations are particularly relevant when considering that the observed changes indicate a general rise in surface temperatures, largely attributed to rapid urban expansion and intensified land conversion that have diminished vegetation cover while increasing impervious surfaces. Such land-use transitions weaken natural cooling mechanisms, especially evapotranspiration, and intensify heat accumulation, thereby reducing overall thermal comfort. This highlights the urgent need for urban development policies in Unaaha to actively integrate and protect green infrastructure as a means to counteract the urban heat burden. Moving forward, future research should employ longitudinal datasets and incorporate socio-economic parameters to develop more holistic and adaptive strategies for managing thermal environments in rapidly urbanizing regions.

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