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Ecophysiological effects of mangrove canopy density on surface thermal conditions in a tropical lagoon ecosystem of Segara Anakan, Indonesia

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[2]Department of Geography Education, Faculty of Teacher Training and Education, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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Abstract. *Aryanto AEP, Herbowo ACF, Mukarromah AN, Aulia AD, Zulfikar AB, Pitoyo A, Setyawan AD. 2025. Ecophysiological effects of mangrove canopy density on surface thermal conditions in a tropical lagoon ecosystem of Segara Anakan, Indonesia. Cell Biol Dev 9: 12-25.* Mangrove forests are ecologically critical coastal ecosystems that regulate local microclimates and buffer against multiple forms of environmental stress. This study investigates the influence of mangrove canopy density on surface thermal dynamics in the climate-sensitive Segara Anakan Lagoon, Cilacap, Indonesia, using satellite-derived indices. Vegetation density was quantified using the Normalized Difference Vegetation Index (NDVI), while Land Surface Temperature (LST) was derived from Landsat 9 thermal imagery. Spatial overlay and statistical correlation of NDVI and LST were employed to delineate thermal stress zones—defined as areas where surface temperatures exceed physiological thresholds for mangrove growth. Results revealed a strong negative correlation between NDVI and LST ($R^2 = 0.68$; Pearson's $r = -0.82$), indicating that denser vegetation corresponds with cooler surface conditions. Zones with NDVI>0.60 typically exhibited temperatures of 23-25°C, while areas with lower canopy density exceeded 25°C. Thermal hotspots were concentrated in southern and central Cilacap, where anthropogenic disturbance has reduced canopy continuity. These findings highlight the ecophysiological importance of maintaining mangrove canopy cover in mitigating thermal stress. The integration of NDVI-LST analysis provides a non-invasive, scalable tool for monitoring vegetation health, supporting targeted restoration, and informing climate adaptation strategies in tropical coastal landscapes.

Keywords: Land surface temperature, mangrove canopy, NDVI, remote sensing, Segara Anakan, thermal stress

INTRODUCTION

Mangrove forests with their unique and complex nature stand out as one of the most ecologically significant vegetation types in tropical coastal zones. They provide crucial ecosystem services such as shoreline stabilization, carbon sequestration, and habitat provision for various biota. These ecosystems are typically located in estuarine and intertidal areas, are the result of a dynamic interaction between freshwater inflows and tidal seawater, creating a productive environment that is both fascinating and crucial for our understanding of coastal ecosystems (Sipayung and Poedjirahajoe 2021). In Indonesia, mangrove forests are widely distributed, and one of the notable mangrove systems is found in the Segara Anakan Lagoon, Cilacap District, Central Java. This region is characterized by brackish water conditions and the convergence of multiple rivers, presenting a complex hydrological and ecological zone that is challenging for further exploration (Ardelia and Fahleny 2023).

The structure and density of mangrove vegetation play a crucial role in regulating microclimatic variables, particularly Land Surface Temperature (LST), which is a key component of local thermal regimes. The dense canopies formed by mangrove trees modulate light interception, air humidity, and evapotranspiration, all of which are physiologically important for plant growth and microclimate regulation (Indrawati et al. 2020; Huang et al. 2024). In high-density stands, shading reduces direct solar radiation and promotes evaporative cooling, which in turn lowers the temperature of the surrounding environment. This significant role of mangroves in regulating microclimatic variables underscores their importance and the need for their conservation. Conversely, mangrove degradation and canopy loss can expose the soil surface, intensify thermal load, and compromise the ecosystem's thermal buffering capacity (Rahaman et al. 2023; Guo et al. 2024).

Recent advances in satellite remote sensing technologies have enabled the simultaneous assessment of vegetation density and surface temperature through vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and thermal infrared data (Malik et al. 2019). NDVI values, derived from the ratio of near-infrared to red reflectance, serve as reliable proxies for plant greenness, biomass, and canopy vigor (Kshetri 2018; Latue et al. 2023). Likewise, thermal bands from sensors such as Landsat's Thermal Infrared Sensor (TIRS) provide high-resolution estimates of LST, allowing researchers to quantify surface thermal variation across vegetation gradients (Fadlin et al. 2020). In coastal ecosystems, the combination of NDVI and LST provides valuable insight into how vegetation structure mediates land-atmosphere interactions.

Although NDVI and LST are widely used for assessing vegetation-environment interactions, fewer studies have focused specifically on the ecophysiological interpretation of mangrove canopy effects on surface thermal regimes in tropical lagoons. Such interpretation is important because changes in surface temperature may alter photosynthetic performance, respiration rates, and water-use efficiency of mangrove species (Alongi 2018; Fazlioglu et al. 2020). Temperature fluctuations can also affect mangrove metabolic rates and nutrient cycling, leading to downstream impacts on forest productivity and resilience. In extreme cases, prolonged exposure to high temperatures can exceed species-specific thermal tolerances, potentially leading to stress, reduced carbon sequestration, or mortality (Li et al. 2015; Segaran et al. 2023).

In the context of climate change, understanding the relationship between vegetation cover and surface thermal dynamics becomes increasingly urgent. Rising global temperatures, coupled with sea level rise and altered precipitation patterns, may compromise the ecological stability of mangrove forests (de Lacerda et al. 2019). In Southeast Asia, mangroves already face pressures from land conversion, aquaculture, and coastal development, which reduce canopy density and exacerbate thermal stress on exposed surfaces (Al Kafy et al. 2021). Mangrove canopy loss not only accelerates surface warming but also limits the forest's ability to moderate air temperatures, store carbon, and regulate favorable conditions for seedling establishment.

In Indonesia, this challenge is addressed by Presidential Regulation No. 73 of 2020 through the national mangrove rehabilitation program led by the Peatland and Mangrove Restoration Agency (BRGM). This policy underscores the need for scalable monitoring tools, where satellite-based indices such as NDVI and LST can help identify canopy degradation and thermal risk zones in support of targeted restoration. Despite their potential, integrated analyses of NDVI and LST in mangrove systems remain limited in Indonesian contexts, particularly in lagoonal environments.

Segara Anakan provides a critical case study for exploring how mangrove canopy structure influences surface thermal conditions under tropical lagoon settings. With large expanses of both intact and degraded mangrove stands, the region allows for spatial comparisons of canopy density and its thermal effects. By examining these patterns, researchers can infer the potential physiological stress gradients experienced by mangrove trees and anticipate changes in ecosystem function. Moreover, such spatial data can inform restoration efforts by identifying priority areas for replanting or protection based on thermal vulnerability.

This study aims to assess the ecophysiological implications of mangrove canopy density on land surface temperature in the Segara Anakan Lagoon. Specifically, it seeks to (i) map vegetation density and surface temperature using remote sensing tools, (ii) analyze the spatial correlation between canopy density and surface thermal gradients, and (iii) discuss the physiological significance of observed patterns for mangrove species. The novelty of this study lies in its integration of satellite-based thermal data with ecophysiological reasoning, highlighting how vegetation structure mediates environmental temperature in tropical coastal forests.

MATERIALS AND METHODS

Study area

The study was conducted in the Segara Anakan Lagoon, located in Cilacap District, Central Java, Indonesia. This lagoon is one of the largest and most dynamic estuarine ecosystems on the southern coast of Java Island. Administratively, the mangrove forest area around Segara Anakan spans several sub-districts, including Kalipucang, Patimuan, Kampung Laut, South Cilacap, and Central Cilacap.

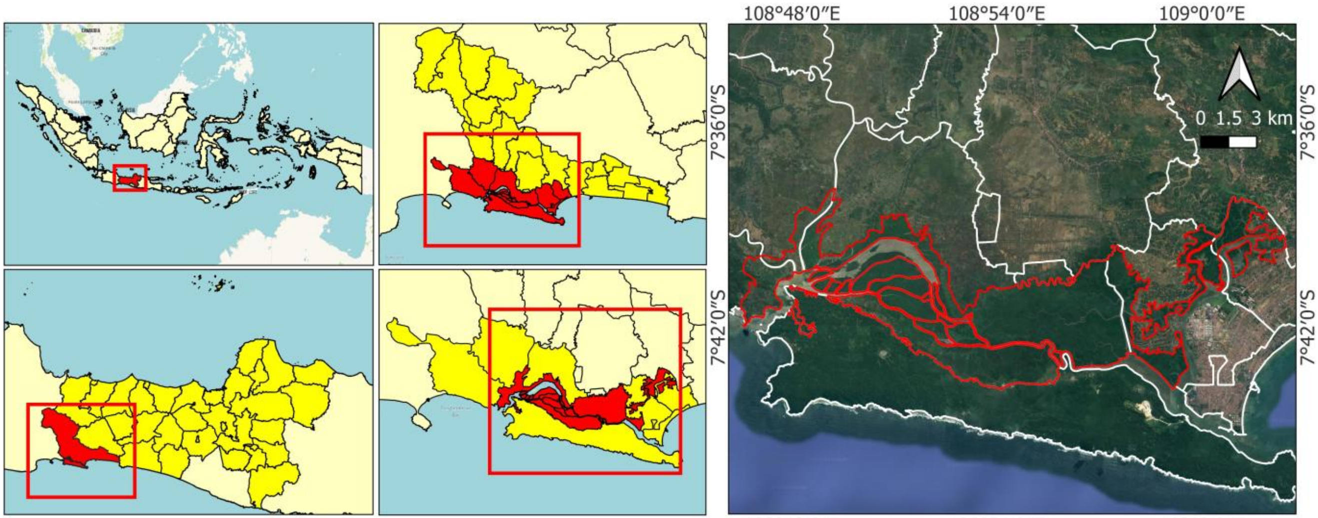

Figure 1. Study area map showing the mangrove region around Segara Anakan Lagoon, Cilacap District, Central Java, Indonesia

Table 1. Geographic coordinates and ecological descriptions of the observed mangrove sub-regions in Segara Anakan Lagoon, Cilacap District, Central Java, Indonesia

Sub-district	Coordinates (Lat, Long)	Key features	Dominant vegetation
Kalipucang	7°38′S, 108°52′E	Fringing mangrove, adjacent to river mouths	*Rhizophora apiculata* Blume
Patimuan	7°40′S, 108°50′E	Mixed mangrove with sediment-rich tidal flats	*Sonneratia alba* Sm.
Kampung Laut	7°43′S, 108°48′E	Dense canopy mangrove, community-managed area	*Avicennia marina* (Forssk.) Vierh.
South Cilacap	7°44′S, 109°00′E	Fragmented mangrove interspersed with settlements	*Bruguiera gymnorhiza* (L.) Lam.
Central Cilacap	7°45′S, 109°02′E	Urban-influenced coastal vegetation	*Avicennia officinalis* L.

Table 2. Summary of Landsat 9 satellite imagery used in the study

Parameter	Description
Satellite / Sensor	Landsat 9 / OLI (Optical), TIRS (Thermal)
Acquisition date	July 2023 (Dry season, minimal cloud cover)
Bands for NDVI	Band 4 (Red), Band 5 (Near Infrared, NIR)
Bands for LST	Band 10 and Band 11 (Thermal Infrared)
Spatial resolution	30 m (Optical and thermal, resampled)
Image pre-processing steps	Radiometric correction, atmospheric correction, and cloud masking
Processing software	QGIS 3.28, ENVI 5.6, Semi-Automatic Classification Plugin

Geographically, the study area lies between latitudes 7°35'-7°50' South and longitudes 108°45'-109°03' East. The region encompasses a complex mosaic of tidal channels, mudflats, and mangrove stands, where the influence of riverine sedimentation and tidal inundation creates favorable conditions for mangrove growth (Hilmi et al. 2022). These environmental gradients contribute to the spatial heterogeneity of canopy structure, vegetation density, and surface temperature observed across the lagoon.

The climate in the study region is tropical monsoonal, with distinct wet and dry seasons. Annual rainfall exceeds 3,000 mm, and the temperature ranges from 25°C to 33°C throughout the year. The mangrove vegetation is dominated by typical Southeast Asian species such as *Rhizophora apiculata*, *Avicennia marina*, and *Sonneratia alba*, which are adapted to saline soils and tidal flooding.

Due to its ecological significance, the Segara Anakan Lagoon has been subject to various conservation, mapping, and monitoring efforts. However, increasing anthropogenic pressure from aquaculture, land reclamation, and sedimentation from upstream rivers has resulted in degradation of some mangrove areas, making it a suitable site for studying vegetation-climate interactions. Figure 1 shows the geographical location and administrative boundaries of the Segara Anakan mangrove region used in this study. Table 1 summarizes the detailed descriptions of the five observed subregions.

Data sources and satellite imagery

This study employed multi-spectral and thermal infrared satellite imagery from the Landsat 9 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) sensors to obtain data on vegetation cover and land surface temperature. Landsat 9 provides free and regularly updated Earth observation data with a spatial resolution of 30 meters for optical bands and 100 meters (resampled to 30 m) for thermal bands, making it suitable for regional-scale environmental analysis (Fadlin et al. 2020).

The imagery used in this study was acquired during the dry season to minimize the influence of cloud cover and seasonal hydrological variability. Dry season imagery ensures clearer spectral readings, especially in mangrove ecosystems where tidal inundation and moisture fluctuations can affect reflectance values. The date of acquisition was selected based on minimal cloud cover (<10%) and data quality checks using pre-processed metadata.

Two sets of spectral data were used for analysis: (i) bands 4 (Red) and 5 (Near-Infrared, NIR) for the calculation of the Normalized Difference Vegetation Index (NDVI), and (ii) bands 10 and 11 (Thermal Infrared) for Land Surface Temperature (LST) estimation. These bands were chosen based on their proven applicability for vegetation and thermal studies in tropical and coastal environments (Kshetri 2018; Malik et al. 2019).

Data pre-processing included radiometric calibration, atmospheric correction, and cloud masking using standardized tools in spatial analysis software. For NDVI calculations, Top-of-Atmosphere (TOA) reflectance values were used, while surface radiance data were extracted from thermal bands for LST computation. All processing steps were conducted using QGIS (version 3.28) and ENVI, complemented by the Semi-Automatic Classification Plugin and raster calculator functions (Table 2).

The spatial extent for image clipping and analysis was defined by the mapped boundary of the Segara Anakan mangrove zone as shown in Figure 1. The zone was digitized from administrative maps and validated using existing shapefiles from the National Mangrove Mapping Project (Hilmi et al. 2022). The final analysis included all terrestrial mangrove areas, excluding open water bodies and urban areas where mangrove vegetation was absent.

NDVI calculation and vegetation density classification

Vegetation density in the Segara Anakan mangrove area was assessed using the Normalized Difference Vegetation Index (NDVI), which is a widely applied spectral index for evaluating vegetation health, canopy cover, and biomass. NDVI is computed from the reflectance values of the Red (R) and Near-Infrared (NIR) bands of satellite imagery, based on the principle that healthy vegetation absorbs red light for photosynthesis and reflects near-infrared light (Kshetri 2018; Malik et al. 2019).

The NDVI value was calculated using the following formula:

$$\text{NDVI} = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:
NIR : Reflectance in near-infrared (Band 5-Landsat 9)
Red : Reflectance in red spectrum (Band 4-Landsat 9)

The resulting NDVI values range from -1 to +1, where higher values (typically >0.6) indicate dense and healthy vegetation, and lower values (<0.2) suggest sparse or degraded cover. Areas with values near zero represent barren land or built-up areas, while negative values indicate water bodies (Latue et al. 2023). For analysis, NDVI values were reclassified into five vegetation density categories based on thresholds modified from previous mangrove classification studies in Indonesia (Hilmi et al. 2022; Mahardianti et al. 2024) (Table 3). The NDVI calculation was performed using raster calculator tools in QGIS and further processed through zonal statistics to determine the total area of each density class. Only vegetated zones within the mangrove polygon boundary were included in this analysis. Open water, exposed mudflats, and anthropogenic structures were masked out during pre-processing to avoid classification errors. The spatial distribution of vegetation density was then visualized through a false-color composite NDVI map, which served as a base for subsequent correlation analysis with land surface temperature (Figure 2).

To address the lack of field-based validation, NDVI classification results were visually compared with high-resolution Google Earth imagery from 2019, focusing on known vegetated and degraded zones within the Segara Anakan Lagoon. This approach provided a basic cross-reference to assess the plausibility of NDVI class boundaries. While this method does not replace quantitative accuracy assessment, it offers a practical means of validating vegetation density interpretation in the absence of comprehensive ground-truth data. The authors acknowledge this as a methodological limitation and recommend future studies incorporate field sampling or very high-resolution imagery for more rigorous classification accuracy assessment.

LST calculation and surface temperature mapping

Land Surface Temperature (LST) was derived from thermal infrared data using the Thermal Infrared Sensor (TIRS) bands of Landsat 9. The thermal bands (Band 10 and Band 11) are sensitive to emitted longwave radiation and are commonly used to estimate surface temperatures, particularly in studies related to vegetation-climate interactions (Fadlin et al. 2020; Mahardianti et al. 2024).

The LST estimation process involved several key steps: (i) conversion of Digital Numbers (DN) to Top-of-Atmosphere (TOA) radiance, (ii) calculation of brightness temperature, (iii) correction for Land Surface Emissivity (LSE), and (iv) transformation to actual surface temperature in degrees Celsius. Emissivity values were estimated based on the Proportion of Vegetation (PV), which was inferred from NDVI values following the method of Malik et al. (2019).

Table 3. NDVI-based classification of vegetation density in Segara Anakan

NDVI range	Vegetation density class	Description
<0.00	Water bodies	Non-vegetated, permanently inundated areas
0.00-0.20	Low density	Degraded mangrove or early regrowth
0.21-0.40	Medium density	Moderately developed canopy
0.41-0.60	High density	Well-established, continuous canopy cover
>0.60	Very high density	Dense mangrove stands with full canopy

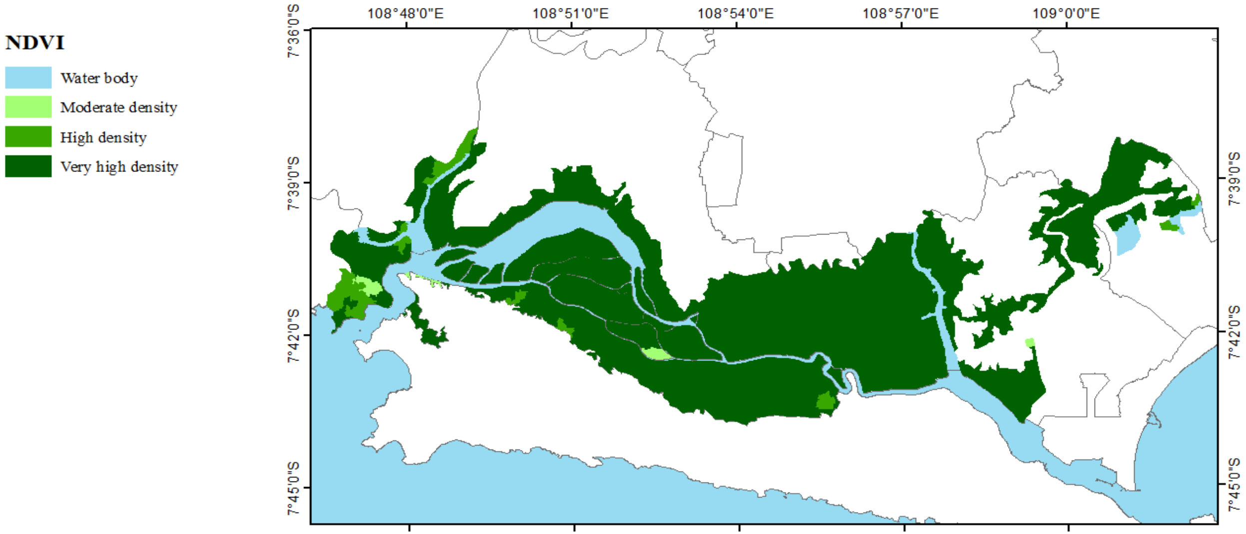

Figure 2. NDVI-based mangrove vegetation density map of Segara Anakan, classified into five density categories

The key formulas used in this process are summarized:
TOA Radiance (Lλ):

$$L_\lambda = M_L \times Q_{cal} + A_L$$

Where:
M_L: Band-specific multiplicative rescaling factor
A_L : Band-specific additive rescaling factor
Q_{cal} : Quantized calibrated pixel values (DN)

Brightness Temperature (BT):

$$BT = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

Where:
K1 and K2 : Band-specific thermal conversion constants

Proportion of Vegetation (PV):

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

Land Surface Emissivity (LSE or ε):

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

LST in Kelvin and conversion to Celsius:

$$LST = \frac{BT}{1 + \left(\frac{\lambda \times BT}{\rho}\right)\ln(\varepsilon)}$$

$$LST(^{\circ}C) = LST(K) - 273.15$$

Where:
λ= Wavelength of emitted radiance (~11.5 μm)
$\rho = h \cdot c/\sigma \approx 1.438 \times 10^{-2}$ m·K
h : Planck's constant
c: speed of light
σ: Boltzmann constant

LST values were calculated per pixel and spatially mapped using GIS-based tools. Water bodies and non-vegetated regions were masked using NDVI thresholds to isolate surface temperature data relevant to mangrove vegetated areas.

The final LST raster was classified into six temperature classes to facilitate comparison across vegetation density gradients and to identify potential thermal hotspots or cool zones. Classification thresholds were set based on the natural breaks in the temperature (Table 4).

The LST classification map shown in Figure 3 visualizes the spatial distribution of surface temperature. This map was used to assess correlations with NDVI classes and interpret ecophysiological implications related to thermal stress.

Table 4. Classification scheme for surface temperature in the study area

Temperature range (°C)	Class	Description
13-18	Very low	Shaded areas, high canopy cover
18.1-21	Low	Dense canopy or water-adjacent zones
21.1-23	Moderate-Low	Stable vegetated surfaces
23.1-24	Moderate	Transitional vegetated-open zones
24.1-25	High	Sparse canopy or disturbed vegetated area
>25	Very high	Bare land or mangrove degradation area

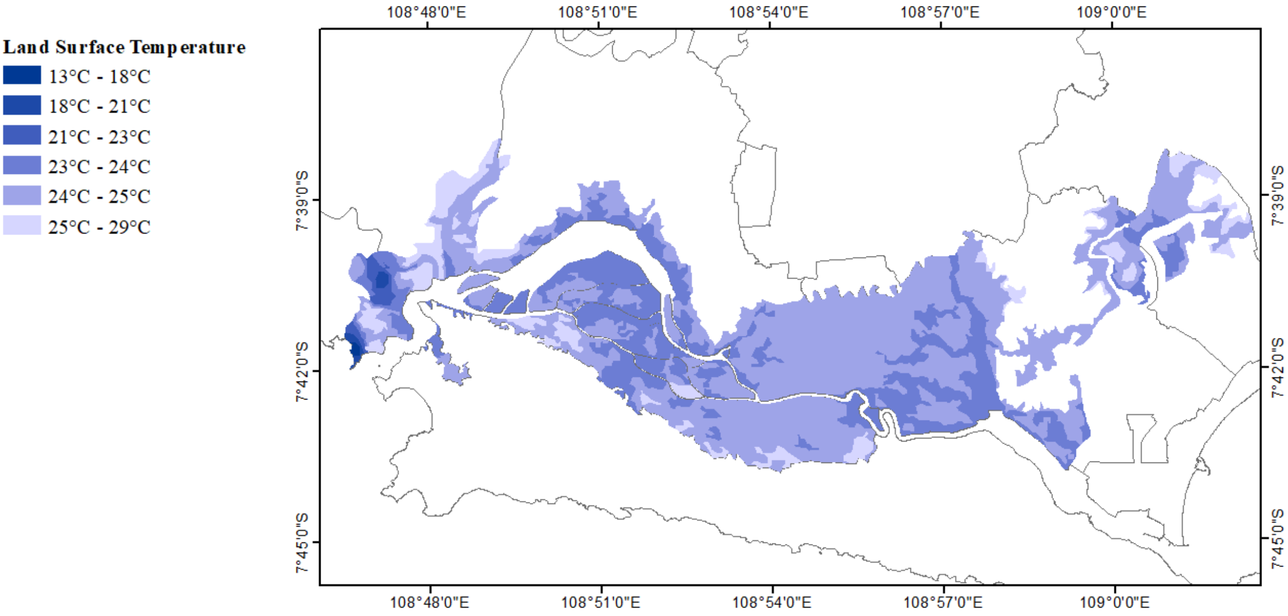

Figure 3. Classified land surface temperature map of Segara Anakan, derived from Landsat 9 thermal bands

Sampling strategy and statistical analysis

To ensure spatially representative and statistically valid results, a stratified random sampling approach based on vegetation density zones derived from the NDVI classification was adopted. This method divides the study area into defined strata—such as water bodies and low, medium, high, and very high vegetation density—and allows for proportionate random sampling within each stratum (Arieska and Herdiani 2018). This strategy enhances analytical robustness by capturing variability across different vegetation conditions in the mangrove ecosystem, significantly enhancing the analytical robustness of the study and providing a comprehensive understanding of the ecosystem.

The number of sampling units (pixels) required from each stratum was determined using the Slovin formula, which is commonly used to calculate sample size when population size is known and a specific margin of error is desired (Madjina et al. 2024):

$$n = \frac{N}{1 + Ne^2}$$

Where:

n : Required sample size

N : Total number of observation units (NDVI pixels)

e : Margin of error (set at 5% in this study)

Using this formula, the total number of pixels to be sampled was computed, then allocated proportionally across strata based on their area coverage (as shown in Table 3). Within each stratum, pixel locations were selected randomly using GIS-based random sampling tools to ensure unbiased representation.

Once sample pixels were selected, NDVI and LST values were extracted for each location and exported for statistical analysis. A linear regression analysis was conducted to test the hypothesis that vegetation density (as indicated by NDVI) has a negative correlation with Land Surface Temperature (LST). This test was chosen due to the continuous and normally distributed nature of both variables and the established theoretical expectation of inverse association (Pramudiyasari et al. 2021; Fitriani et al. 2023).

The statistical model used was:

$$LST = \beta_0 + \beta_1 \cdot NDVI + \varepsilon$$

Where:

LST : Land Surface Temperature (°C)

NDVI : Normalized Difference Vegetation Index

β : Intercept

$\beta 1$: Regression coefficient

ε: Error term

The coefficient of determination (R^2), p-value, and regression slope were used to evaluate the strength and significance of the relationship. In addition, Pearson's correlation coefficient (r) was calculated to further describe the direction and magnitude of association between NDVI and LST values.

All statistical analyses were conducted using IBM SPSS Statistics and validated using R (version 4.2) for cross-verification. Prior to model fitting, data were tested for normality, linearity, and homoscedasticity to satisfy the assumptions of linear regression. Outliers and anomalies were addressed through residual diagnostics and visual inspection of scatterplots.

Data interpretation and ecophysiological inference

The integration of spatial analysis and statistical modeling in this study aimed not only to quantify the relationship between vegetation density and Land Surface Temperature (LST), but also to provide a physiologically meaningful interpretation of the results. Specifically, NDVI was interpreted as a proxy for canopy vigor, Leaf Area Index (LAI), and photosynthetic potential, while LST served as an indicator of thermal stress in the mangrove ecosystem (Alongi 2018; Fazlioglu et al. 2020).

High NDVI values are commonly associated with dense and healthy mangrove canopies, which exert a cooling influence on surface temperatures through shading and evapotranspiration. These processes reduce incoming solar radiation at the ground level and enhance latent heat flux, both of which contribute to lower LST (Indrawati et al. 2020; Neinavaz et al. 2020). In contrast, areas with low NDVI—typically reflecting sparse vegetation or disturbed zones—exhibit reduced evapotranspiration rates and greater exposure to solar radiation, resulting in elevated LST values.

By statistically correlating NDVI and LST values, it is possible to infer the degree to which canopy structure modulates microclimatic conditions, particularly in terms of thermal buffering. This is especially relevant in tropical lagoon ecosystems like Segara Anakan, where mangroves are exposed to intense solar radiation and fluctuating tidal moisture regimes. A strong negative correlation between NDVI and LST would support the hypothesis that vegetation density plays a vital role in mitigating surface heat.

Beyond physical interpretation, these patterns also carry ecophysiological significance. Lower surface temperatures in densely vegetated mangrove zones may promote optimal conditions for photosynthesis, reduce transpiration-driven water loss, and protect plants from thermal damage (Saintilan et al. 2014; Segaran et al. 2023). Inversely, higher LST values may induce physiological stress, alter stomatal behavior, and increase respiration rates, potentially reducing net primary productivity in vulnerable stands (de Lacerda et al. 2019).

These implications are particularly important in the context of climate change, where high surface and ambient temperatures may push mangrove species beyond their physiological tolerance limits. Therefore, the spatial interaction between NDVI and LST revealed in this study not only reflects surface conditions but also serves as an indirect indicator of plant physiological health and ecosystem stability.

In summary, this methodological framework—linking remote sensing-derived vegetation indices and thermal data—provides a valuable tool for assessing ecophysiological conditions in mangrove landscapes. It can be extended to support long-term monitoring, restoration planning, and vulnerability assessment under scenarios of global warming and anthropogenic disturbance.

RESULTS AND DISCUSSIONS

NDVI-derived mangrove vegetation density

The spatial distribution of mangrove vegetation in Segara Anakan was assessed using the Normalized Difference Vegetation Index (NDVI), which effectively captures canopy density and greenness. NDVI values in the study area ranged from below 0.00 (water bodies) to above 0.60 (very dense vegetation), reflecting varying levels of canopy closure across the lagoon landscape.

Based on the NDVI classification thresholds established in the methodology (Table 3), five distinct vegetation density classes were identified: water bodies, low, medium, high, and very high vegetation density. The reclassified NDVI map revealed that the majority of the mangrove area in Segara Anakan fell into the "Very High Density" category.

Table 5 summarizes the areal coverage of each NDVI class, while Figure 2 visualizes the spatial pattern of mangrove vegetation density. Table 5 shows that approximately 84.1% of the mangrove zone exhibited NDVI values >0.60, while 8.5% fell within the Low Density class (NDVI 0.00-0.20), indicating sparse or regenerating canopy zones. This revision aligns the vegetation classification with the observed extent of thermal stress zones, strengthening the spatial interpretation of canopy-related microclimatic variation.

The map vividly demonstrates the significance of the very high-density vegetation zone forming a contiguous green belt along the inner lagoon and estuarine margins. This belt, particularly concentrated in Kampung Laut and Patimuan sub-districts, plays a crucial role in the health and stability of the mangrove ecosystem. Areas of medium or high density, while more fragmented, also contribute to the overall balance, often occurring near anthropogenic edges or in recently disturbed sites.

The dominance of very high NDVI values across the landscape not only suggests favorable growth conditions but also hints at the potential for high photosynthetic productivity in most parts of the mangrove forest. The spatial presence of medium-density patches, while indicating the existence of transitional or regenerating stands, also presents an opportunity for further growth and regeneration, even in the face of thermal stress or anthropogenic pressure.

Land surface temperature distribution

Land Surface Temperature (LST) across the Segara Anakan mangrove landscape was extracted from Landsat 9 thermal bands and classified into six categories to represent varying degrees of surface heat intensity. The temperature values ranged from 13°C to just under 29°C, with most areas concentrated in the moderate to high temperature range. The LST classification was based on the natural breaks observed in the temperature histogram and is summarized in Table 6. The corresponding LST distribution map is presented in Figure 3.

As shown in Table 6, the largest portion of the area (~61.5%) falls within the 24.1-25°C class, while ~27.7% lies in the 23.1-24°C range. These two classes combined account for nearly 90% of the total study area, indicating a relatively consistent thermal regime across most of the vegetated surface.

The highest temperature zones (>25°C), which represent 998 ha or 9.5% of the area, are spatially concentrated near degraded or edge habitats. Conversely, zones with lower surface temperatures (<23°C) comprise only a minor fraction of the landscape (1.4%), typically corresponding to areas with dense vegetation or persistent shading.

The overall distribution suggests a strong moderation of surface temperature by vegetation cover, but also highlights localized warming in areas with reduced canopy or altered land cover. These thermal gradients provide the basis for further analysis of vegetation-temperature interactions in the subsequent sections.

Spatial overlay of vegetation density and surface temperature

To examine the spatial correspondence between mangrove vegetation density and Land Surface Temperature (LST), an overlay analysis was performed by intersecting the NDVI-based vegetation classification map with the LST classification map. This approach allowed the identification of spatial patterns where canopy density and thermal characteristics co-occur, revealing zones of thermal resilience or vulnerability across the mangrove landscape.

Table 5. Areal distribution of mangrove vegetation density classes in Segara Anakan based on NDVI values (revised)

Vegetation density class	NDVI range	Area (ha)	Proportion of total area (%)
Water bodies	<0.00	384	3.65
Low density	0.00-0.20	894	8.51
Medium density	0.21-0.40	48	0.46
High density	0.41-0.60	348	3.31
Very high density	>0.60	8,836	84.08
Total	—	10,510	100.00

Table 6. Areal distribution of classified surface temperature zones in Segara Anakan

Temperature class	Temperature range (°C)	Area (ha)	Proportion of total area (%)
Very low	13-18	10	0.10
Low	18.1-21	41	0.39
Moderate-Low	21.1-23	96	0.91
Moderate	23.1-24	2,906	27.65
High	24.1-25	6,459	61.45
Very high	>25	998	9.50
Total	—	10,510	100.00

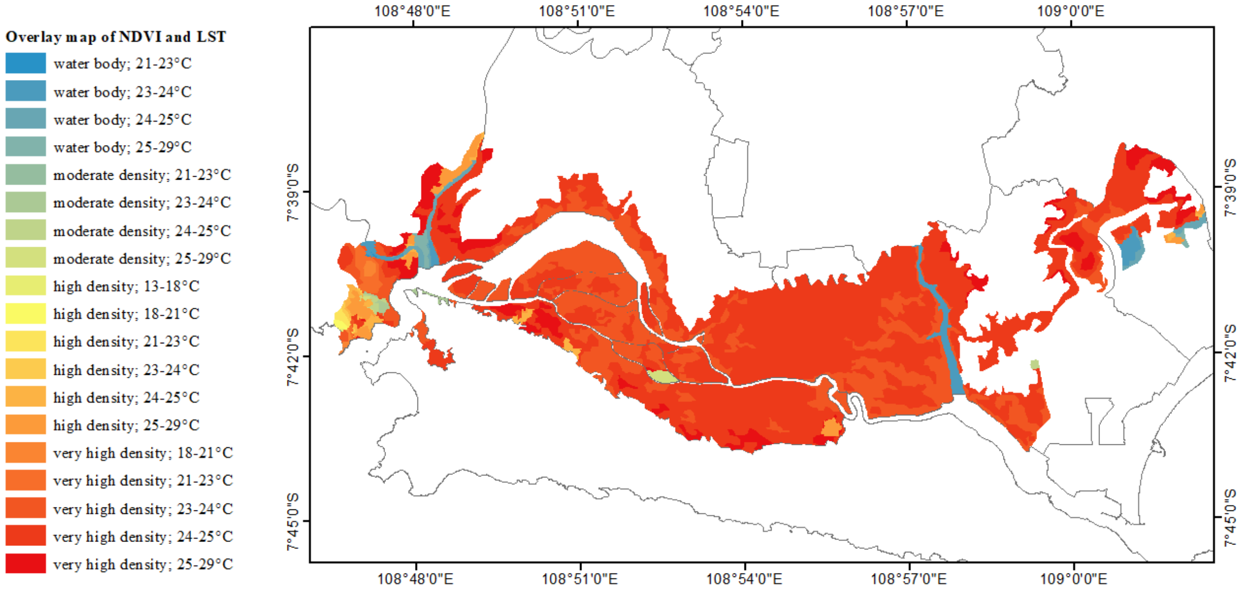

Figure 4. Overlay map of vegetation density (NDVI) and surface temperature (LST) classes in the Segara Anakan mangrove area

Table 7. Overlay table

Overlay	Area (ha)	%
Water body; 21-23°C	2.23	0.02%
Water body; 23-24°C	222.59	2.11%
Water body; 24-25°C	120.24	1.14%
Water body; 25-29°C	42.10	0.40%
Moderate density; 21-23°C	0.10	0.00%
Moderate density; 23-24°C	25.12	0.24%
Moderate density; 24-25°C	25.74	0.24%
Moderate density; 25-29°C	32.79	0.31%
Very high density; 23-24°C	9.06	0.09%
High density; 13-18°C	0.99	0.01%
High density; 18-21°C	11.01	0.10%
High density; 21-23°C	15.74	0.15%
High density; 23-24°C	10.71	0.10%
High density; 24-25°C	105.78	1.00%
High density; 25-29°C	203.65	1.93%
Very high density; 18-21°C	29.96	0.28%
Very high density; 21-23°C	78.11	0.74%
Very high density; 23-24°C	2,647.82	25.10%
Very high density; 24-25°C	6,246.12	59.21%
Very high density; 25-29°C	719.42	6.82%

Figure 4 displays the result of the spatial overlay, highlighting the interaction between vegetation density (five NDVI classes) and surface temperature (six LST classes). The spatial overlay facilitated pixel-wise analysis and visual differentiation of cool-dense zones (e.g., very high NDVI + moderate LST) from hot-sparse zones (e.g., medium NDVI + very high LST). Table 7 summarizes the area coverage of each NDVI-LST class combination. The data show that areas with very high vegetation density (NDVI>0.60) are predominantly associated with moderate (23-24 °C) and high (24-25°C) temperature classes, covering 25.10% and 59.21% of the landscape, respectively. This pattern indicates that dense mangrove canopy helps buffer surface temperature, likely through shading, evapotranspiration, and humidity retention, although the thermal reduction effect may be constrained under intense tropical solar radiation.

In contrast, zones with moderate vegetation density (NDVI 0.21-0.40), though limited in area, tend to align with higher LST categories, including the very high temperature class (>25°C). These transitional areas are commonly found near settlements, along tidal creek margins, or in recently disturbed patches, and appear more susceptible to heat accumulation due to reduced canopy cover.

Water bodies (NDVI<0) consistently register lower LST values (13-21°C), reflecting the high specific heat capacity and evaporative potential of aquatic surfaces. These features act as natural thermal sinks and contribute to local microclimate stabilization.

While the overall pattern confirms a negative spatial correlation between vegetation density and surface temperature, some anomalies were detected. A small proportion of pixels with very high NDVI values coincided with unexpectedly elevated LST (25-29°C), particularly in open or exposed zones. These exceptions may result from local geomorphological variations, surface albedo differences, or anthropogenic disturbances—such as vegetation clearance or infrastructure intrusion—that are not captured by NDVI classification alone.

In summary, the spatial overlay supports the hypothesis that intact mangrove canopy plays a critical role in mitigating surface thermal stress. Areas with continuous vegetation cover demonstrate reduced temperature variability, whereas fragmented or low-density zones exhibit elevated thermal exposure. This spatial insight provides a strong visual and quantitative foundation for the correlation analysis discussed in the subsequent section.

Table 8. Linear regression results: NDVI as predictor of LST

Parameter	**Value**
Regression coefficient (β_1)	-6.82
Intercept (β_0)	27.44
Coefficient of determination (R^2)	0.68
p-value	< 0.001
Pearson's r	-0.82

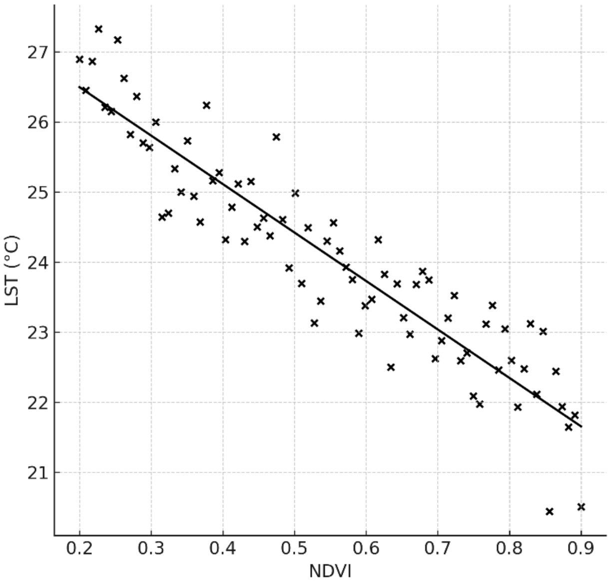

Figure 5. Scatterplot and linear regression line showing the relationship between NDVI and LST in Segara Anakan

Statistical correlation between NDVI and LST

To quantitatively assess the relationship between vegetation density and Land Surface Temperature (LST), a linear regression analysis was conducted using NDVI as the independent variable and LST as the dependent variable. This analysis aimed to validate the spatial trend observed in previous sections, where denser vegetation appears to correlate with lower surface temperatures across the Segara Anakan mangrove ecosystem.

A total of 250 stratified random sample points were extracted from the NDVI-LST overlay map, ensuring balanced representation across vegetation and temperature classes. The scatterplot of NDVI versus LST (Figure 5) shows a strong negative linear trend, indicating that increases in NDVI values are associated with decreases in surface temperature.

The results of the linear regression analysis are presented in Table 8. The model yielded a negative regression coefficient ($\beta_1 = -6.82$), indicating that for every unit increase in NDVI, LST decreases by approximately 6.82°C. The regression model explains 68% of the total variance in surface temperature ($R^2 = 0.68$), and the association is statistically significant ($p<0.001$). Pearson's correlation coefficient further confirms a strong inverse relationship ($r = -0.82$).

These results support the hypothesis that vegetation density, as indicated by NDVI, plays a critical role in modulating surface thermal conditions. Areas with low or medium NDVI tend to accumulate more heat due to reduced shading and evapotranspiration, while densely vegetated mangrove zones act as thermal buffers by lowering surface temperatures and stabilizing microclimates.

The statistical strength and ecological relevance of this relationship emphasize the importance of preserving mangrove canopy cover to reduce localized thermal stress and enhance ecosystem resilience. Further ecological interpretations and conservation implications of these findings are discussed in the next section.

Identification of thermal stress zones

Based on the spatial overlay and regression results, specific zones within the Segara Anakan mangrove landscape were identified as areas of potential thermal stress. These zones are defined by the co-occurrence of low to medium NDVI values (≤0.40) and high to very high land surface temperature (LST≥25°C), indicating insufficient canopy coverage and increased surface heating.

Figure 6 presents the spatial distribution of these zones, delineating thermally vulnerable patches where mangrove vegetation may be exposed to ecophysiological strain. These hotspots correspond spatially with areas classified as Low Density (NDVI 0.00-0.20), reinforcing their role as loci of microclimatic instability and physiological stress.

The overlay analysis identified approximately 927 hectares—or 8.8% of the total mangrove area—as falling within thermal stress zones. These areas are not evenly distributed, with the majority located in South Cilacap and Central Cilacap sub-districts, regions historically subjected to intense anthropogenic pressures such as aquaculture expansion, unregulated shoreline alteration, and resource extraction (Table 9).

To complement the tabular data, Figure 7 provides a visual summary of thermal stress distribution across sub-districts, illustrating both the absolute area and relative proportion of vulnerable mangrove zones.

Table 9. Thermal stress zone extent by sub-district

Sub-district	**Thermal stress area (ha)**	**Percentage of sub-district mangrove area (%)**
Kalipucang	42	3.7
Patimuan	65	5.2
Kampung Laut	71	4.6
South Cilacap	356	18.9
Central Cilacap	393	21.4
Total	927	8.8

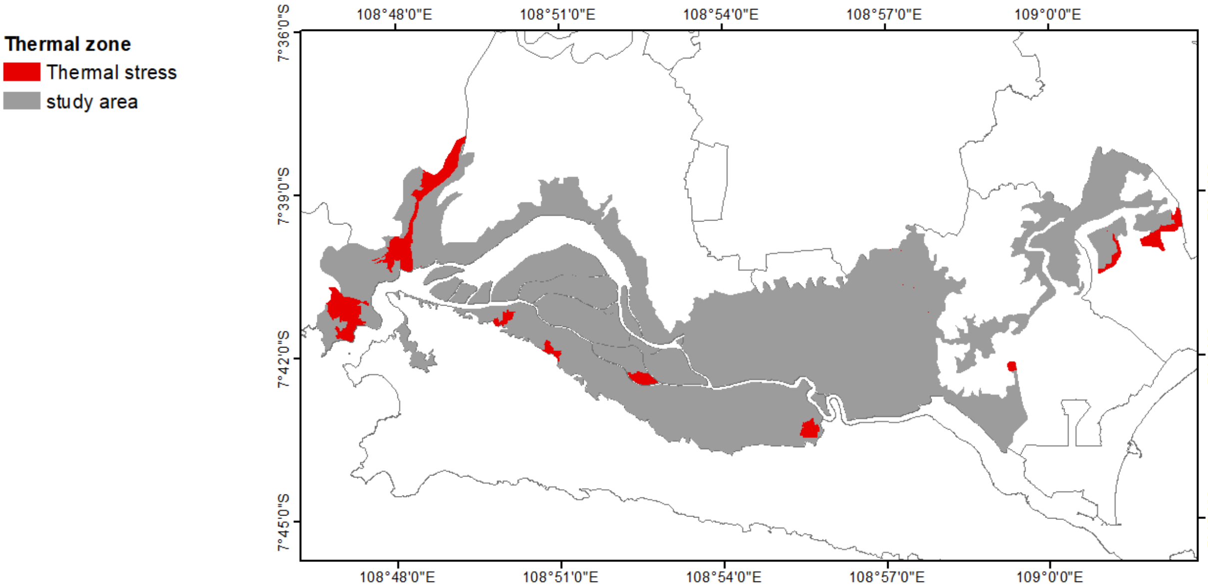

Figure 6. Spatial distribution of potential thermal stress zones in the Segara Anakan mangrove area, based on integrated NDVI-LST thresholds

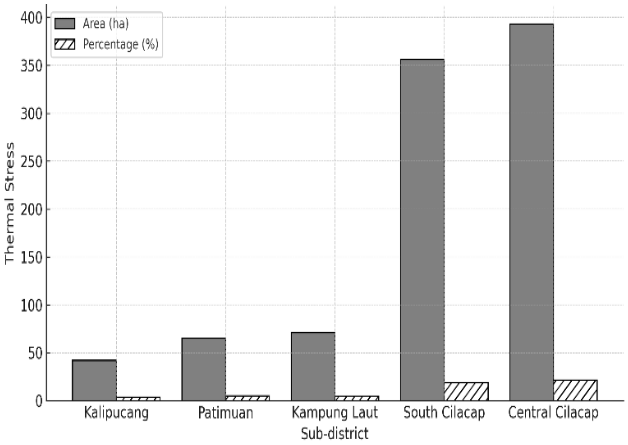

Figure 7. Thermal stress zones in Segara Anakan by sub-district, represented in both absolute area (hectares) and relative percentage of mangrove coverage. Gray bars denote area (ha), while hatched bars indicate percentage (%)

These findings underscore the uneven vulnerability of the Segara Anakan mangrove system. While high canopy density dominates the region, marginal and fragmented stands remain susceptible to thermal stress, particularly during dry seasons or under projected climate change scenarios. These zones are ecophysiologically vulnerable due to increased evapotranspiration demands, reduced stomatal efficiency, and impaired seedling establishment.

Identifying these thermal hotspots is essential for informing spatially targeted mangrove management strategies. Interventions such as canopy gap restoration, enrichment planting, and shoreline rehabilitation in these zones could significantly enhance the thermal resilience and long-term ecological functionality of the mangrove ecosystem.

Discussion

Influence of vegetation density on surface temperature

The results of this study demonstrate a strong and consistent negative correlation between vegetation density, as measured by NDVI, and Land Surface Temperature (LST) across the Segara Anakan mangrove ecosystem. Areas with very high NDVI values (>0.60), which reflect dense mangrove canopy cover, were predominantly associated with moderate surface temperatures (23-25°C), while areas with medium NDVI values exhibited higher LST (>25°C). This inverse relationship is supported by both visual spatial analysis (overlay maps) and quantitative regression results, with Pearson's $r = -0.82$ and $R^2 = 0.68$, indicating that vegetation density accounts for a substantial proportion of surface thermal variation.

The underlying mechanism of this relationship lies in the physical properties of dense mangrove canopies, which influence microclimatic conditions through shading and evapotranspiration. Dense canopy structures intercept a significant fraction of incoming solar radiation, thereby reducing the amount of energy that reaches and is absorbed by the soil or surface beneath (Indrawati et al. 2020). This interception function effectively lowers the ground-level radiant energy load and limits heat accumulation, resulting in cooler surface conditions.

In addition to shading, mangrove vegetation contributes to surface cooling via evapotranspiration, a process in which water is transferred from soil and plant tissues to the atmosphere. Through this process, latent heat is consumed, which further decreases the surrounding air and surface temperature (Neinavaz et al. 2020; Fitriani et al. 2023). In regions with high NDVI values, evapotranspiration rates tend to be higher due to greater leaf area and stomatal activity, both of which enhance the cooling capacity of the ecosystem.

This thermoregulatory function of mangrove vegetation has been documented in various coastal and estuarine environments globally. This research has significant practical implications, as it provides a scientific basis for the conservation and restoration of mangrove ecosystems. Forested zones consistently exhibit lower surface temperatures than adjacent deforested or degraded areas (Al Kafy et al. 2021; Guo et al. 2024); a pattern observed in the context of Segara Anakan. This research underscores the pivotal role of vegetation cover in maintaining surface temperature stability in tropical lagoon ecosystems, a finding that can guide real-world conservation efforts.

Interestingly, a few areas with very high NDVI values were also associated with relatively elevated LST levels. These localized anomalies may be attributed to factors such as slope orientation, soil albedo, or anthropogenic disturbance (e.g., recent clearing or infrastructure development), which could override the cooling effects of dense canopy cover. Such deviations highlight the complexity of surface energy dynamics and the need for fine-scale spatial analysis.

The absence of low-density vegetation zones (NDVI<0.2) in this study is notable. It suggests that either such areas are minimal in extent or have transitioned into non-vegetated categories such as exposed soil, settlements, or open water. These surfaces, lacking both canopy and evapotranspiration potential, tend to exhibit elevated LST values due to unmitigated solar absorption.

In summary, the findings confirm that mangrove canopy density exerts a significant biophysical influence on surface thermal dynamics, functioning as a natural buffer against heat accumulation. Preserving and enhancing vegetation density, particularly in edge and transition zones, is thus essential not only for ecological integrity but also for regulating microclimatic stability in tropical coastal environments.

Ecophysiological implications of thermal variation

Beyond its physical effects on microclimate, surface temperature variation has important ecophysiological consequences for mangrove species, particularly in zones exposed to persistent thermal stress. As observed in this study, areas with reduced vegetation density were consistently associated with elevated surface temperatures (>25°C), a threshold that may exceed the physiological tolerance range of several dominant mangrove taxa (Fazlioglu et al. 2020; Segaran et al. 2023).

High temperatures can affect mangrove physiology by altering key processes such as photosynthesis, respiration, and stomatal regulation. Elevated leaf temperatures disrupt enzymatic processes involved in carbon fixation, leading to reduced photosynthetic efficiency. At the same time, thermal stress increases respiration rates, which in turn causes a net carbon loss that compromises plant growth and biomass accumulation (Alongi 2018).

Moreover, higher temperatures increase Vapor Pressure Deficit (VPD), intensifying water loss through transpiration and imposing greater demands on plant water-use efficiency. In mangrove species, particularly those in fringe and degraded zones with limited freshwater availability, this condition may lead to osmotic imbalance, cellular dehydration, and reduced turgor pressure, ultimately lowering survival probability under prolonged heat stress (Field 1995; de Lacerda et al. 2019). Such stress is often compounded by concurrent salinity pressure, further narrowing the physiological buffer range available to these species.

Thermal variation also indirectly affects nutrient cycling and microbial activity in mangrove soils, which are tightly linked to vegetation productivity and resilience. High temperatures can shift microbial community composition, affect litter decomposition rates, and alter nitrogen and phosphorus availability, thereby impacting root function and nutrient uptake (Segaran et al. 2023). Such changes may have cascading effects on seedling establishment, canopy regeneration, and overall forest structure.

In this context, the spatial pattern of thermal stress zones mapped in Segara Anakan may signal early stages of physiological degradation or delayed regeneration, particularly in areas with a history of disturbance or incomplete canopy recovery. The dense canopy areas in Segara Anakan that maintain moderate surface temperatures are likely to provide a more stable physiological environment for mangrove trees, promoting sustained gas exchange, efficient water use, and optimal metabolic function. In contrast, thermally stressed zones—identified in this study as areas with medium NDVI and very high LST—represent ecophysiological risk zones where productivity and long-term viability may be impaired.

Therefore, understanding the thermal landscape of mangrove ecosystems is not merely a climatological concern but a direct proxy for plant health and ecological function. The integration of NDVI and LST provides a non-destructive, scalable approach to assess ecophysiological conditions across large spatial extents, especially in resource-limited or monitoring-deficient mangrove regions. By identifying biophysically stressed zones early, managers can intervene proactively to prevent irreversible degradation and guide strategic restoration planning.

Spatial vulnerability and restoration priorities

The spatial overlay of vegetation density and surface temperature has enabled the identification of thermally vulnerable zones within the Segara Anakan mangrove ecosystem. These zones are characterized by medium NDVI values (0.21-0.40) and elevated LST (>25 °C), suggesting patches of fragmented canopy or incomplete regeneration under disproportionate thermal load. Such areas, though limited in extent (~8.8% of the total study area), represent ecologically significant targets for restoration due to their susceptibility to stress and their capacity to serve as critical thermal buffers if rehabilitated.

Sub-districts such as South Cilacap and Central Cilacap exhibited the highest concentrations of thermal stress zones, likely due to their proximity to urban development, infrastructure, and altered hydrological regimes. These peripheral and transitional areas often experience higher anthropogenic pressure, including logging, aquaculture, and land conversion, which reduce canopy density and expose the substrate to solar heating (Al Kafy et al. 2021; Rahaman et al. 2023).

Prioritizing these thermally stressed areas for restoration offers dual benefits: improving local microclimate stability and enhancing the physiological resilience of mangrove stands. Reforestation with native, heat-tolerant species such as *Avicennia marina* or *Sonneratia alba* could accelerate canopy closure, increase evapotranspiration capacity, and reduce surface temperatures over time. Such actions would not only restore vegetation structure but also mitigate further degradation driven by climate-induced warming.

Furthermore, spatially explicit restoration planning allows for efficient resource allocation by focusing efforts on the most vulnerable zones rather than uniform interventions across the landscape. This targeted strategy aligns with adaptive ecosystem-based management approaches and supports Indonesia's national agenda for coastal resilience and blue carbon conservation (Hilmi et al. 2022).

Integrating thermal vulnerability mapping into mangrove rehabilitation programs also provides a science-based rationale for monitoring the effectiveness of restoration efforts over time. Changes in NDVI and LST can serve as measurable indicators of ecological recovery and ecosystem service enhancement, particularly in terms of temperature regulation, carbon storage, and habitat stabilization.

Identifying and mapping spatial thermal vulnerability in Segara Anakan thus provides not only a diagnostic tool but also an operational pathway for planning ecologically and physiologically grounded restoration. These thermally exposed areas should be recognized as conservation priorities to prevent further canopy loss and to maintain the functional integrity of coastal vegetation under increasing climate pressures.

Integrating remote sensing for ecophysiological monitoring

Remote sensing has emerged as a valuable tool in assessing vegetation health and environmental stress, particularly in complex and inaccessible ecosystems such as mangrove forests. In this study, the integration of NDVI and LST metrics derived from Landsat 9 imagery enabled a spatially explicit, landscape-level assessment of vegetation structure and surface thermal dynamics in Segara Anakan. This approach provides an indirect but powerful means of inferring ecophysiological conditions without destructive sampling or intensive ground measurements.

NDVI serves as a reliable proxy for canopy greenness, biomass, and photosynthetic activity, while LST reflects the surface energy balance influenced by vegetation cover, moisture, and solar radiation. The strong inverse relationship between these two indices, confirmed through regression analysis, validates their combined use in identifying areas of physiological stress and microclimatic regulation (Malik et al. 2019; Pramudiyasari et al. 2021). This relationship is particularly valuable in tropical estuarine systems where direct physiological measurements are logistically challenging.

The spatial resolution and repeatability of satellite data make it well-suited for long-term monitoring, allowing researchers and managers to detect changes in canopy condition and thermal exposure over time. For example, declines in NDVI coupled with rising LST may signal degradation, canopy loss, or reduced evapotranspiration—conditions that warrant ecological intervention. Conversely, increasing NDVI and cooling trends may indicate successful restoration or natural regeneration. This capacity to detect directional trends enables remote sensing to function as an early-warning system for ecosystem stress.

Despite its strengths, remote sensing also presents limitations in ecophysiological interpretation. While NDVI and LST provide valuable surrogates, they do not directly measure physiological parameters such as chlorophyll fluorescence, stomatal conductance, or sap flow. Thus, field validation and integration with ground-based measurements remain essential, especially for species-specific assessments or detecting early sublethal stress. A hybrid monitoring approach that combines satellite-derived indices with in situ ecological data would enhance diagnostic precision.

Moreover, satellite data may be affected by atmospheric interference, cloud cover, and sensor calibration differences, which require careful pre-processing and quality control. In coastal environments, the presence of mixed pixels (e.g., water-land interface) may also reduce classification accuracy and necessitate masking techniques or higher-resolution imagery. The dynamic tidal regime in estuarine zones further complicates classification and calls for temporal filtering or multi-date compositing.

Nonetheless, the synergy between NDVI and LST represents a practical and scalable framework for ecophysiological monitoring in mangrove systems. By capturing vegetation-temperature interactions, this method contributes to a better understanding of forest health dynamics, supports restoration planning, and informs adaptive management in the face of climate variability. As climate impacts intensify, such integrative remote sensing approaches will be indispensable in guiding evidence-based interventions for coastal ecosystem resilience.

Broader implications under climate change

The findings of this study offer important insights into the role of mangrove canopy structure in mitigating thermal stress, which is directly relevant to broader climate change dynamics in tropical coastal ecosystems. As global temperatures continue to rise and sea levels increase, mangrove forests face heightened exposure to thermal extremes, salinity fluctuations, and hydrological instability (Saintilan et al. 2014; de Lacerda et al. 2019).

Surface warming threatens the physiological performance of mangrove species and undermines their capacity to deliver key services such as carbon sequestration, shoreline protection, and fisheries support. Elevated LST can impair photosynthetic function, increase respiration rates, and reduce the net primary productivity of mangrove stands, thereby weakening their ability to act as carbon sinks and climate buffers (Alongi 2018; Fazlioglu et al. 2020). Such disruptions not only affect individual tree health but can scale up to compromise ecosystem service delivery.

Moreover, increased thermal exposure may exacerbate the vulnerability of mangroves to other climate-related stressors, including more frequent droughts, intensified storms, and saltwater intrusion. These compound threats can lead to shifts in species composition, migration of physiological limits, and in some cases, collapse of fringe mangrove belts—especially in areas where anthropogenic disturbance has already fragmented canopy cover (Field 1995; Li et al. 2015). The interaction between climate forcing and local degradation accelerates ecological decline, often beyond natural recovery thresholds.

The identification of thermally vulnerable zones in Segara Anakan highlights the importance of spatially targeted adaptation strategies. Maintaining dense vegetation cover in key buffer zones may offer a low-cost, ecosystem-based solution to limit microclimatic instability and support resilience under future warming scenarios. Restoration programs that prioritize degraded hotspots, as revealed through NDVI-LST analysis, can enhance thermal regulation and promote landscape-scale ecosystem stability. This highlights the operational utility of spatial diagnostics in directing resource-efficient adaptation measures.

In a policy context, integrating remote sensing indicators like NDVI and LST into climate vulnerability assessments can strengthen early warning systems and inform national strategies such as Indonesia's National Adaptation Plan (NAP) or REDD+ initiatives. Furthermore, these findings align with global conservation frameworks such as the UN Decade on Ecosystem Restoration, which emphasizes the importance of nature-based solutions to climate resilience. Such alignment reinforces the relevance of local-scale evidence to international climate agendas.

The spatial coupling of vegetation density and surface temperature thus functions not only as an ecological diagnostic tool but also as a foundation for implementing adaptive, climate-informed mangrove management. By understanding how canopy structure modulates thermal stress, stakeholders can implement more responsive and science-based actions to sustain coastal forest health in a warming world.

In conclusion, this study demonstrates that mangrove canopy density exerts a critical influence on surface temperature regulation within the Segara Anakan estuarine ecosystem. A strong inverse relationship between NDVI and LST—where high NDVI values correspond with cooler surface temperatures—highlights the thermoregulatory function of dense vegetation. Areas with low to medium NDVI values (≤0.40) exhibited disproportionately high LST (>25 °C), with the majority of thermally stressed zones corresponding to the Low Density class. This reinforces the need to monitor and restore sparse canopy areas as part of climate-sensitive mangrove management. The spatial overlay of NDVI and LST enabled the identification of ecophysiologically vulnerable hotspots, primarily concentrated in South and Central Cilacap sub-districts. These findings support the strategic use of satellite-derived indicators for targeting mangrove restoration and adaptive management. NDVI-LST integration offers a scalable and non-destructive tool to monitor degradation risks and climate sensitivity, reinforcing the importance of preserving canopy continuity. Strengthening mangrove cover is vital not only for biodiversity and carbon sequestration, but also for mitigating surface heat extremes and sustaining ecosystem services in the face of climate change.

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