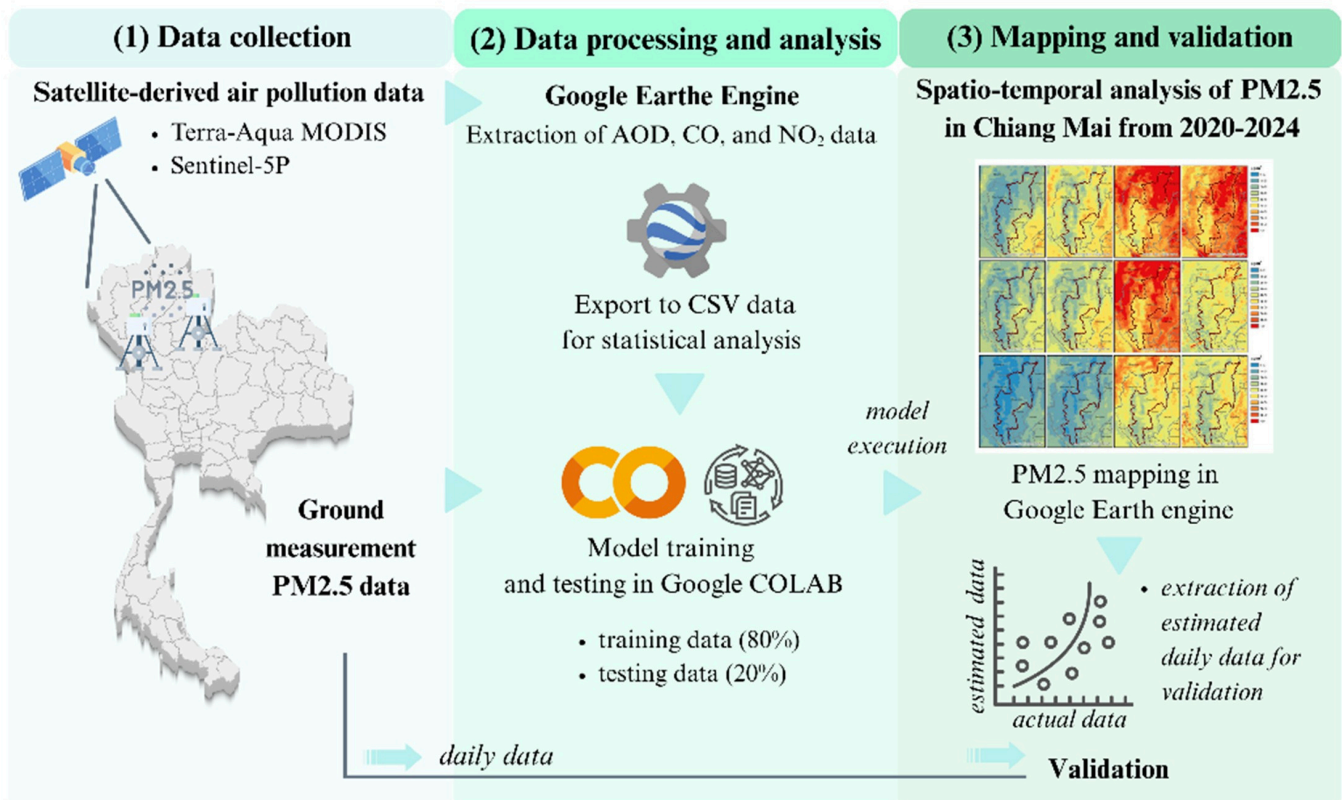




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Spatio-temporal distribution of PM2.5 over Chiang Mai Province, Thailand, from 2020 to 2024. Surface-level PM2.5 concentrations were estimated by integrating ground-based measurements and satellite observations using multiple linear regression (MLR) in Google Earth Engine.

Source: Suppawimut W, Hemwan P, Thavorntam W, Charoenpanyanet A. Spatio-temporal analysis of PM2.5 concentrations through integration of aerosol optical depth and Sentinel-5P data using google earth engine. Environ. Nat. Resour. J. 2026;24(4):382-396.



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Spatio-Temporal Analysis of PM_{2.5} Concentrations through Integration of Aerosol Optical Depth and Sentinel-5P Data Using Google Earth Engine

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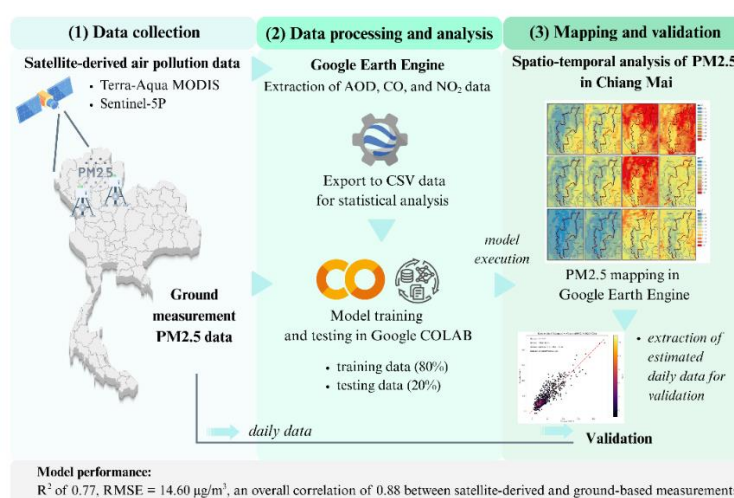
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Aerosol optical depth

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ABSTRACT

GRAPHICAL ABSTRACT



Air pollution in Northern Thailand is a persistent environmental issue, particularly during the dry season, posing significant health risks. This study used multiple remote-sensing data sources to explore spatio-temporal PM_{2.5} variations in Chiang Mai Province from 2020 to 2024. Ground-based PM_{2.5} measurements were merged with Terra-Aqua aerosol optical depth (AOD) and Sentinel-5P carbon monoxide (CO) and nitrogen dioxide (NO₂) data within the Google Earth Engine platform. Multiple linear regression models were employed to estimate ground-level PM_{2.5} concentrations and generate spatial distribution maps. Central lowland and northern areas of Chiang Mai consistently exhibited higher PM_{2.5} levels, particularly in March and April. The model achieved an R² of 0.77 and a root mean square error (RMSE) of 14.60 µg/m³, with an overall correlation of 0.88 between satellite-derived and ground-based measurements. Seasonal analysis revealed enhanced model performance during the burning period (January-April; R²=0.72, RMSE=17.31 µg/m³), compared with the non-burning period (May-December; R²=0.26, RMSE=8.32 µg/m³). During the 2020-2024 burning periods, average PM_{2.5} concentrations were 51.33, 45.62, 25.18, 49.81, and 41.11 µg/m³, respectively, peaking at 79.18±16.90 µg/m³ in March 2023. Integrating AOD with Sentinel-5P CO and NO₂ data improved estimation accuracy and hotspot identification, highlighting the potential of cloud-based geospatial platforms for comprehensive air quality monitoring.

HIGHLIGHTS

- Multi-source satellite data integration (AOD, CO, NO₂) within the Google Earth Engine successfully estimated PM_{2.5} concentrations, achieving high accuracy R²=0.77, RMSE=14.60 µg/m³, and R=0.88 correlation.
- Model performance showed significant seasonal variation, with higher accuracy during burning periods (R²=0.72) versus non-burning periods (R²=0.26), while combining aerosol and gas species data from TROPOMI substantially improved estimation over AOD-only models.
- This cloud-based remote sensing approach effectively mapped PM_{2.5} hotspots, demonstrating strong potential for air quality monitoring in areas with limited ground-based measurements.

Citation: Suppawimut W, Hemwan P, Thavorntam W, Charoenpanyanet A. Spatio-temporal analysis of PM_{2.5} concentrations through integration of aerosol optical depth and Sentinel-5P data using google earth engine. Environ. Nat. Resour. J. 2026;24(4):382-396. (<https://doi.org/10.32526/ennrj/24/20250246>)

1. INTRODUCTION

Air pollution, specifically fine particulate matter (PM_{2.5}), is a critical environmental issue in Thailand, significantly impacting public health (Chankaew et al., 2022). According to the Pollution Control Department (2023), annual average PM_{2.5} concentrations from 87 stations nationwide ranged from 12 to 49 $\mu\text{g}/\text{m}^3$, with many stations exceeding the national average of 26 $\mu\text{g}/\text{m}^3$. This issue is particularly severe in Northern Thailand during the dry season. Epidemiological studies have consistently demonstrated associations between elevated PM_{2.5} levels and respiratory and cardiovascular diseases (Buya et al., 2026; Fatima et al., 2023). Notably, Sapbamrer et al. (2024) revealed direct associations between short-term PM_{2.5} exposure and COPD fatality rates in the north of Thailand, while Buya et al. (2026) found significant correlations between monthly PM_{2.5} levels and cardiorespiratory mortality during 2015-2019.

Agricultural residue burning and forest fires are the primary pollution sources in Northern Thailand, particularly during the dry season (Junpen et al., 2018; Paluang et al., 2024). Road transportation is another major contributor, with traffic emissions accounting for 76% (27.2 $\mu\text{g}/\text{m}^3$) of PM_{2.5} during the non-burning period in Chiang Mai (Chansuebsri et al., 2024). This proportion decreased to 13% during the burning period, when biomass burning became predominant (51%). Transboundary pollution and limited public transportation development also create significant barriers to effective air quality management (Bran et al., 2022; Chansuebsri et al., 2024).

Ground-based PM_{2.5} measurements are essential for air quality monitoring and health impact assessment (Holloway et al., 2021). However, the insufficient number and poor distribution of monitoring stations limit spatial coverage, resulting in data gaps in rural regions affected by biomass burning (Son et al., 2023; Song et al., 2019). Accurate and spatially extensive PM_{2.5} estimation is crucial for addressing these limitations and enhancing exposure assessments (Chen et al., 2018).

Satellite-based remote sensing is essential for wide spatial coverage. Previous studies have derived surface PM_{2.5} from aerosol optical depth (AOD), employing methodologies including statistical regression (Hands Schuh et al., 2022) and machine learning (Song et al., 2025; Wongnakae et al., 2023). However, processing these multi-temporal satellite datasets requires substantial computational resources.

Google Earth Engine (GEE) has emerged as a prominent cloud-based platform that mitigates this challenge by enabling efficient analysis of petabyte-scale geospatial data without the need for high-performance local infrastructure. Recent studies have demonstrated its effectiveness in spatio-temporal air quality monitoring and pollutant mapping (Ghasempour et al., 2021; Paluang et al., 2024; Rirugchart et al., 2025).

Despite these advancements, localized studies considering region-specific characteristics are still critically needed (Pardthaisong et al., 2018). Chiang Mai is characterized by seasonal biomass burning, basin topography, and specific meteorology, creating a complex context that requires specialized approaches. This study examines the spatio-temporal distribution of PM_{2.5} in Chiang Mai from 2020 to 2024 by integrating ground data with satellite AOD, CO, and NO₂ data using multiple linear regression (MLR) within GEE. It aims to clarify spatial distribution patterns in unmonitored areas, offering a framework applicable to different contexts and providing spatial data for epidemiological research and air pollution monitoring.

2. METHODOLOGY

2.1 Study area

The study area is Chiang Mai Province, located in Northern Thailand between latitudes 17°14' and 20°8'N and longitudes 98°00' and 99°34'E, covering approximately 20,107 km² with a 2024 population of 1.79 million (Chiang Mai Provincial Statistical Office, 2024). The terrain is predominantly mountainous with central lowlands, with an average annual temperature of 25.4°C (range: 20.1-31.8°C). This basin-shaped topography (Figure 1) restricts atmospheric ventilation during biomass burning, exacerbating pollutant accumulation and public health risks (Chansuebsri et al., 2024). The study area and the distribution of air quality monitoring stations are illustrated in Figure 1.

2.2 Data collection

2.2.1 Ground-based PM_{2.5}

Daily average PM_{2.5} concentrations from 2020 to 2024 were obtained from nine air quality monitoring stations, provided by the Pollution Control Department of Thailand (PCD). Due to the limited number of ground monitoring stations in Chiang Mai, the dataset includes measurements from PM_{2.5} stations located in both Chiang Mai (35T and 36T) and neighboring provinces: Lampang (37T and 40T),

Chiang Rai (57T and 73T), Mae Hong Son (58T), Lamphun (68T), and Tak (76T). The MLR model uses this data as its dependent variable (Y). Details and sources of the data are presented in Table 1. Prior to analysis, the ground-based PM_{2.5} data underwent quality control, with missing data, zeros, and invalid values removed from the dataset.

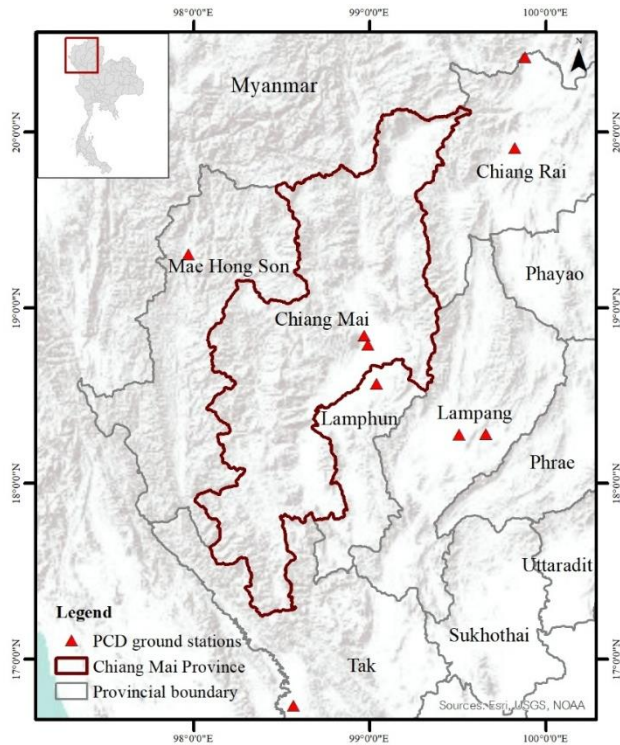


Figure 1. Map of the study area covering Chiang Mai Province and neighboring provinces in Northern Thailand, showing the locations of air quality ground stations.

2.2 Data collection

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2.2.2 Aerosol optical depth

AOD is a unitless measure of aerosols distributed within a column of air from Earth's surface to the top of the atmosphere. In this study, the Level 2 AOD product was obtained from the combined Terra and Aqua MODIS sensors using the Multi-angle Implementation of Atmospheric Correction (MAIAC) algorithm (MCD19A2). Crucially, this algorithm offers a fine spatial resolution of 1×1 km², which has been shown to significantly improve the characterization of PM_{2.5} spatial distribution compared with coarser datasets (Holloway et al., 2021; Rirugchart et al., 2025; Song et al., 2025). The 0.55 µm band of this AOD data for ground-based PM_{2.5} monitoring locations, serving as the primary independent variable in the model, was extracted using GEE.

2.2.3 TROPOMI

Sentinel-5P is an air quality monitoring satellite developed by the European Space Agency as part of the Copernicus Programme. It carries the Tropospheric Monitoring Instrument (TROPOMI), which measures atmospheric chemical concentrations at high resolution. TROPOMI daily data of carbon monoxide (CO) and nitrogen dioxide (NO₂) were retrieved from GEE at 1×1 km² grid (Table 1). CO and NO₂ have been effectively utilized in air pollution studies to identify areas with elevated biomass burning and traffic emissions, respectively (Pathakoti et al., 2021; Sakti et al., 2023).

Table 1. List of datasets used in this study

Data	Variables	Units	Temporal resolution	Data source
Ground-based PM _{2.5} (2020-2024)	Daily average PM _{2.5}	µg/m ³	Daily	PCD, Thailand
MODIS AOD (2020-2024)	Optical depth at 0.55 µm	Unitless	Daily	GEE
Sentinel-5P: CO (2020-2024)	CO column number density	mol/m ²	Daily	GEE
Sentinel-5P: NO ₂ (2020-2024)	NO ₂ column number density	mol/m ²	Daily	GEE

2.3 Data processing

A multi-phase methodology was used to estimate PM_{2.5} in Chiang Mai Province and parts of

Northern Thailand, employing remote sensing data and ground-based observations within a cloud-based framework. GEE served as the primary platform for

data extraction and satellite data processing, while Python (Google Colab) was used for regression model development.

The initial phase involved daily extraction of satellite data from 2020 to 2024. In the GEE environment, we retrieved AOD at 0.55 μm from the MCD19A2 product and CO and NO₂ column number densities from Sentinel-5P (TROPOMI). These variables were sampled at nine PCD PM2.5 ground monitoring stations, resulting in a daily paired dataset of satellite-derived atmospheric properties and ground-measured PM2.5 observations across Chiang Mai and neighboring provinces, with days containing missing AOD or TROPOMI data excluded. The data were then exported as CSV files for model training.

The second phase focused on regression model development. An MLR model was developed in Google Colab to quantify the relationship between ground-measured PM2.5, AOD, CO, and NO₂. Predictor variables (AOD, CO, and NO₂) were used in their raw satellite-derived units to maintain physical interpretability and ensure compatibility with operational satellite inputs. Model performance was evaluated using R² and root mean square error (RMSE). The resulting coefficients were applied within the GEE environment to generate PM2.5 maps. Following the statistical framework established in previous satellite-based air quality studies (Hands Schuh et al., 2022; Kaewmesri et al., 2024), the estimation model was expressed as:

$$\text{Estimated PM2.5} = \beta_0 + \beta_1 \cdot \text{AOD} + \beta_2 \cdot \text{CO} + \beta_3 \cdot \text{NO}_2 \quad (1)$$

Where; estimated PM2.5 represents the predicted PM2.5 concentration. β_0 is the intercept, representing the baseline PM2.5 concentration when all satellite-derived variables are zero. AOD, CO, and NO₂ are the AOD, CO, and NO₂ column number densities, respectively, obtained from satellite observations. β_1 , β_2 , and β_3 are the regression coefficients for AOD, CO, and NO₂, respectively.

The final phase involved daily PM2.5 estimation and monthly averaging. Using GEE, the regression model was applied to every pixel across the study area to generate daily estimates from 2020 to 2024. Model performance was evaluated against PCD ground data using R² and RMSE. To mitigate short-term variability and data discontinuities in daily satellite measurements, daily estimates were averaged into monthly maps. The analysis focused on the “burning period” (January-April), corresponding to

peak biomass-burning activity. Seasonal averages were calculated using GEE’s mean reducer function for all pixels within Chiang Mai Province. While this study presents maps covering adjacent areas for regional comparison, statistical values were calculated exclusively within Chiang Mai. Future research will use these data to analyze PM2.5 drivers and assess the associated health impacts in Chiang Mai Province.

3. RESULTS AND DISCUSSION

3.1 Statistical analysis

A total of 5,377 valid daily records combining AOD, CO, and NO₂ satellite data with ground-measured PM2.5 daily data were obtained for analysis, with dates containing any missing values excluded. Correlation analysis demonstrated statistical relationships ($p < 0.001$) between ground PM2.5 and all three predictive variables. CO showed the strongest positive correlation with PM2.5 ($r = 0.82$), followed by AOD ($r = 0.72$) and NO₂ ($r = 0.32$) (Figure 2). This finding is consistent with the results of Amnuaylojaroen (2022), who demonstrated a strong correlation between CO and PM2.5 levels in Chiang Mai Province. To ensure the stability of the regression model, variance inflation factors (VIFs) were calculated to detect potential multicollinearity among the predictor variables. The VIF values for AOD, CO, and NO₂ were 3.36, 3.47, and 1.10, respectively, all well below the critical threshold of 5 (Hair et al., 2019), indicating negligible multicollinearity and reliable model coefficients.

The synchronization between satellite-derived precursors and ground-level PM2.5 is strongest during intense burning episodes (February-April). This high temporal covariance is attributed to the co-emission of aerosols and trace gases from biomass-burning activity, which is the dominant source during this period (Junpen et al., 2018; Paluang et al., 2024). Furthermore, stable atmospheric conditions and low planetary boundary layer height (PBLH) during the dry season simultaneously trap these pollutants, reinforcing their correlation. In contrast, this temporal coupling weakens during the wet season due to precipitation scavenging (washout) and a shift toward traffic-dominated emissions, for which the ratio of PM2.5 to gaseous precursors differs from that associated with biomass burning.

In the multiple regression analysis, the 5,377 observations were divided into two subsets: 80% (4,301 observations) for model training and 20% (1,076 observations) for testing and validation. A

regression model was generated by iteratively adding and removing predictor variables and evaluating performance using R² and RMSE for each dataset

combination. The regression results are presented in Table 2.

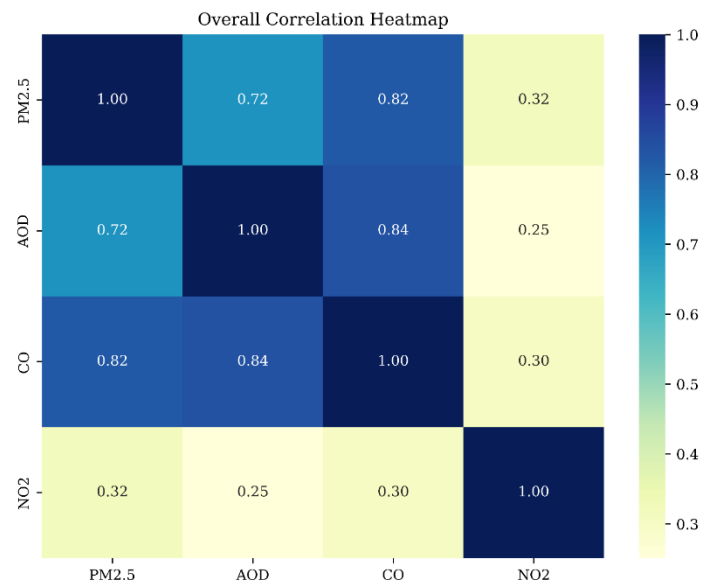


Figure 2. Correlation matrix between PM2.5, AOD, CO, and NO₂

Table 2. Result of regression analysis for different dataset combinations

Variables	R ²	RMSE	p
AOD	0.48	25.30	0.00
AOD+CO	0.65	20.83	0.00
AOD+NO ₂	0.50	24.86	0.00
CO+NO ₂	0.65	20.68	0.00
AOD+CO+NO ₂	0.66	20.66	0.00

The combined dataset of AOD, CO, and NO₂ showed the best performance, with R² and RMSE of 0.66 and 20.66 µg/m³, compared with 0.48 and 25.30 µg/m³ for AOD alone, respectively (Table 2). This result indicates an improvement when incorporating TROPOMI data to estimate ground-based PM2.5. This

finding is consistent with research conducted by Amnuaylojaroen (2022), Han et al. (2022), and Son et al. (2023), who employed Sentinel-5P satellite data for PM2.5 estimation. The estimation model is formally expressed as:

Estimated PM2.5 = (12.48 · AOD) + (1862 · CO) + (87188.97 · NO₂) – 54.51 (2)

Where; estimated PM2.5 represents the predicted PM2.5 concentration (µg/m³). AOD is the aerosol optical depth (unitless), and CO and NO₂ are the total vertical column densities in moles per square meter (mol/m²). All three predictor variables contribute positively to the estimation of PM2.5 concentrations. The relatively large coefficients for CO and NO₂ reflect their small value ranges rather than greater importance. Therefore, due to differences

in variable scales and units, coefficient magnitudes should not be interpreted as indicators of variable importance. These findings are consistent with previous studies (Lalitaporn and Boonmee, 2019; Tan et al., 2024), which also highlight the relevance of trace gases in satellite-based PM2.5 estimation.

To assess model robustness, a temporal validation was conducted by training the model on 2020-2023 data to estimate PM2.5 concentrations for

2024. The results confirmed the superior performance of multi-variable integration (AOD, CO, NO₂) over the AOD-only approach. The integrated model achieved R² of 0.73 and RMSE of 17.37 µg/m³,

whereas the single-variable model yielded a lower R² of 0.58 and a higher RMSE of 21.687 µg/m³, demonstrating a significant reduction in overestimation (Figure 3).

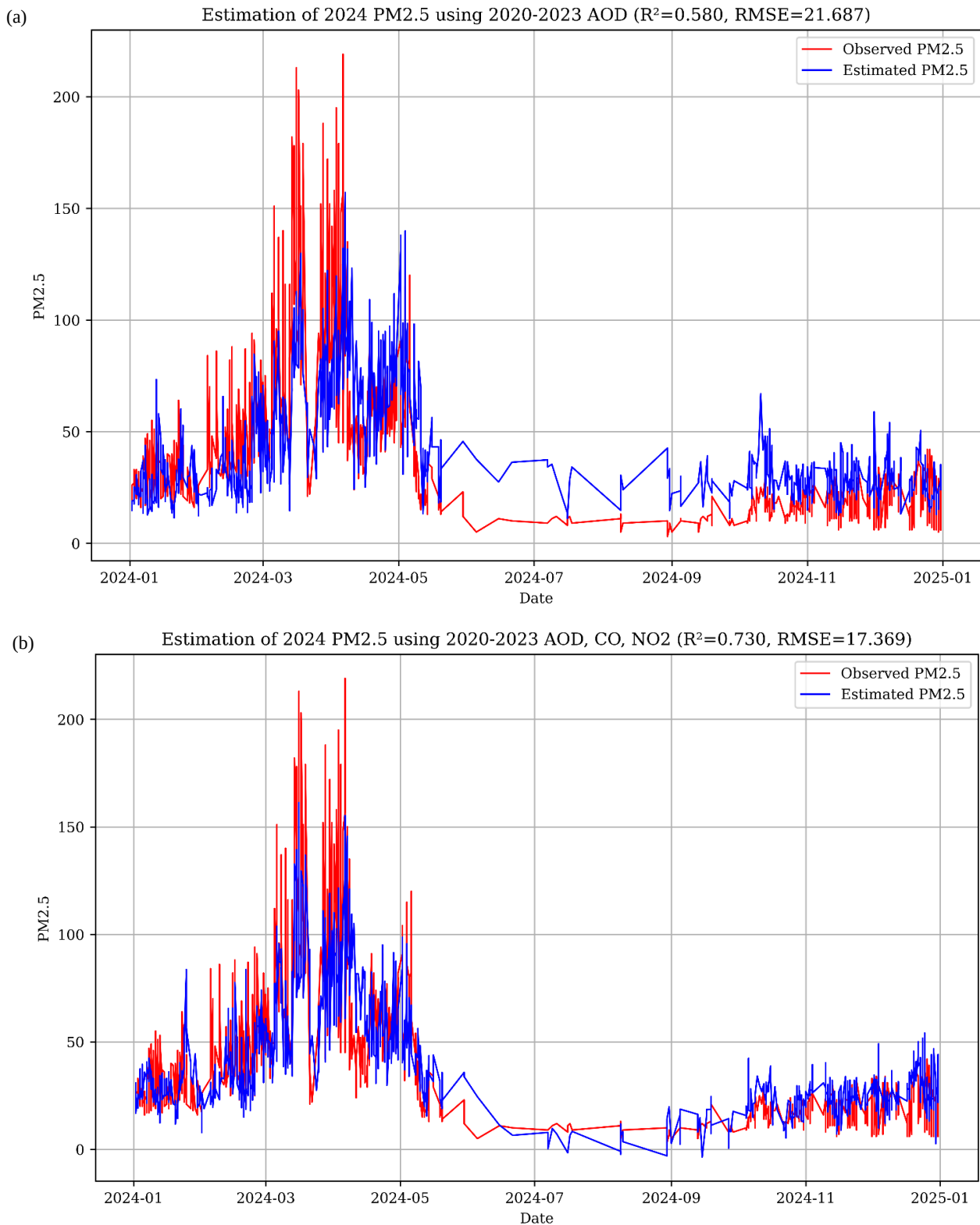


Figure 3. Comparison of ground-observed and estimated PM_{2.5} concentrations (µg/m³) in 2024, based on model trained with 2020-2023 data using (a) AOD only and (b) a combination of AOD, CO, and NO₂

3.2 Estimation of ground PM2.5 in GEE

Within the GEE environment, Equation 2 was applied to estimate daily PM2.5 concentrations (2020-2024). Validation against ground stations (35T and 36T) demonstrated robust overall performance ($r=0.88$, $R^2=0.77$, $RMSE=14.60 \mu g/m^3$). Analysis of the regression parameters ($y=0.91x + 5.55$) revealed range-specific behavior: the positive intercept (+5.55) indicates minor overestimation at low concentrations ($<25 \mu g/m^3$), likely due to surface reflectance interference, while the slope of 0.91 suggests slight underestimation at high concentrations ($>100 \mu g/m^3$), consistent with AOD saturation. Despite these biases, the model maintains high accuracy in the moderate range ($25\text{-}100 \mu g/m^3$), where most observations occur (Figure 4).

To further investigate bias patterns, a residual analysis was performed (Figure S1). The plot reveals a distinct funnel-shaped pattern indicative of heteroscedasticity, with prediction-error variance increasing with PM2.5 concentration. At lower estimated values ($<25 \mu g/m^3$), the residuals are tightly clustered with a slight negative skew, consistent with the model's tendency to overestimate under clean conditions. In contrast, higher concentrations exhibit significantly larger residuals in both directions. While the regression slope (0.91) suggests a general underestimation trend, the residual analysis highlights that prediction uncertainty is markedly higher during peak pollution events.

Compared with results from previous studies in the region, our MLR approach utilizing TROPOMI precursors (CO , NO_2) demonstrates competitive accuracy. While some machine learning-based studies have reported slightly higher correlations ($R^2>0.80$) (Son et al., 2023; Wongnakae et al., 2023), our model offers greater interpretability. For example, Buakhao (2023) used ground-based AERONET AOD in Chiang Mai and reported comparable R^2 values (0.76-0.81) but lower RMSE ($\sim 9.5 \mu g/m^3$). While their ground-based method offers higher precision at specific locations, our satellite-based approach achieves similar predictive performance ($R^2=0.77$) with the added benefit of region-wide spatial coverage, enabling pollution mapping in unmonitored border areas. These results confirm the model's robustness for estimating ground-level PM2.5 in areas with limited ground monitoring.

The implementation of this study within GEE proved to be an effective analytical strategy, enhancing data accessibility and processing efficiency. Its cloud-based computing infrastructure enabled rapid processing of large satellite datasets, establishing it as a powerful platform for environmental monitoring (Ghasempour et al., 2021; Rirugchart et al., 2025). The capacity to retrieve and archive extensive historical air pollution data is another key advantage, enabling historical evaluation in areas without ground-based sensors and supporting comprehensive long-term air quality assessments (Holloway et al., 2021; Wongnakae et al., 2023).

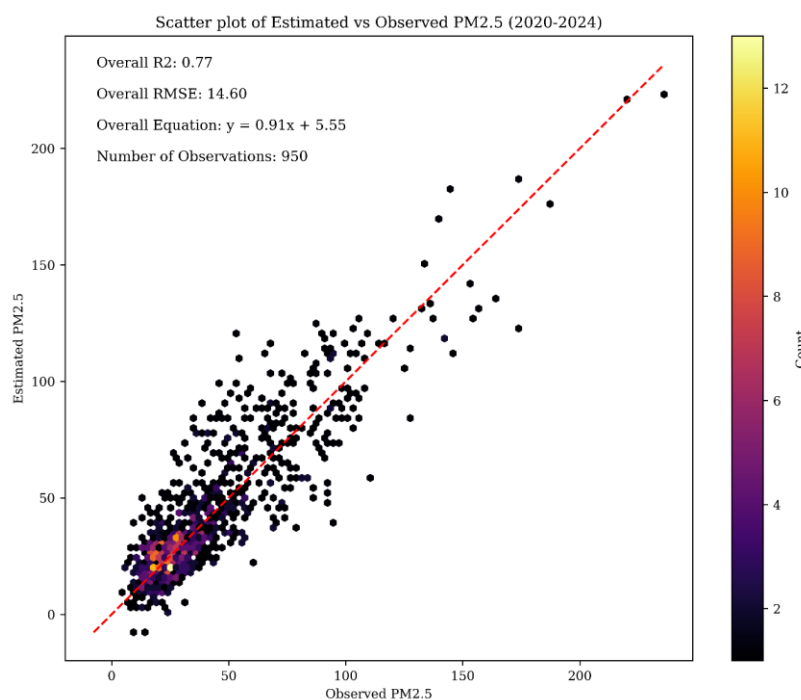


Figure 4. Scatter plot comparing estimated and observed PM2.5

A significant difference in PM_{2.5} estimation model performance was observed between the burning (January-April) and non-burning (May-December) periods. During the burning period, the model demonstrated high accuracy ($R^2=0.72$, RMSE=17.31 $\mu\text{g}/\text{m}^3$; Figure 5(a)), whereas performance declined substantially during the non-burning period ($R^2=0.26$, RMSE=8.32 $\mu\text{g}/\text{m}^3$; Figure 5(b)). This difference highlights the model's stronger predictive capacity

during periods of intensive biomass burning. Consequently, subsequent mapping and analysis focused exclusively on the burning period, when air pollution most strongly affects regional public health, while maps for the non-burning period were excluded due to poor model performance. In addition, extensive missing data caused by cloud cover and rainfall further limited estimation reliability (Son et al., 2023). These issues represent key limitations of the present study.

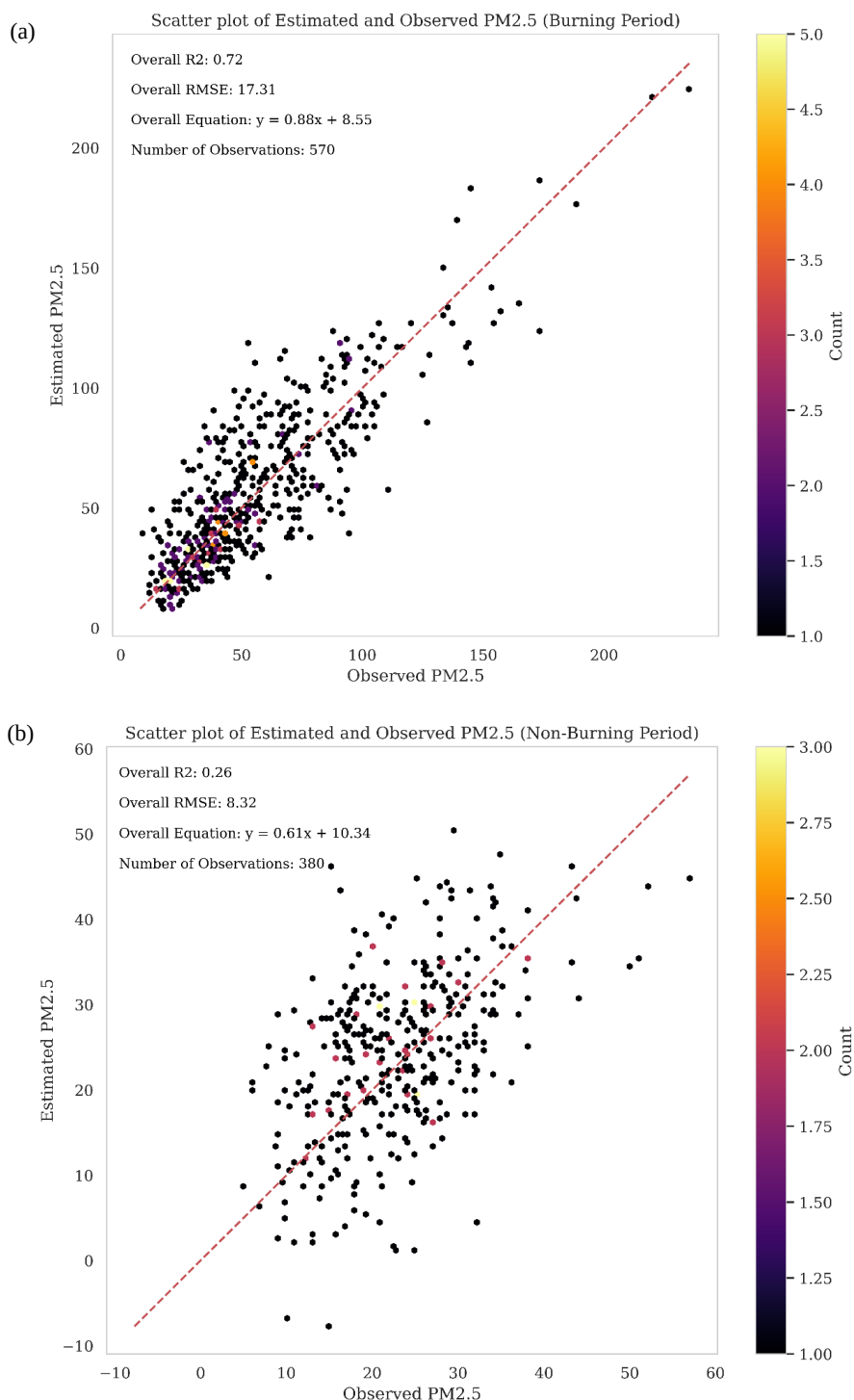


Figure 5. Scatter plot comparing observed and estimated PM_{2.5}: (a) burning period and (b) non-burning period

3.3 Spatio-temporal pattern of PM_{2.5} over Chiang Mai and parts of Northern Thailand

Monthly average PM_{2.5} maps for January-April from 2020 to 2022 are presented in Figures 6 and 7. January consistently exhibited low concentrations across Chiang Mai Province, with mean values of 24.44, 27.11, 11.12, 17.30, and 16.74 $\mu\text{g}/\text{m}^3$, respectively, all within the PCD's standard for good air quality. PM_{2.5} concentrations increased markedly during March and April, particularly in the northern and northeastern regions, where mountainous terrain limits atmospheric ventilation. This temporal surge aligns with Paluang et al. (2024), who identified that forest fire emissions in Upper Northern Thailand reach their peak intensity during these two months. Border districts, such as Chai Prakan and Mae Ai, were particularly affected by both domestic and transboundary biomass burning (Figures 6 and 7). This pattern is consistent with Amnuaylojaroen et al.

(2020) and Chansuebsri et al. (2024), whose WRF-HYSPLIT simulations indicated that transboundary transport from neighboring countries contributes more than domestic sources to PM_{2.5} levels in Northern Thailand.

Figures 6 and 7 show a consistent spatial pattern, with higher values observed in the central and northern parts of Chiang Mai Province. The central part, which includes the provincial center (Mueang District) and several densely populated districts, is the primary residential and urban area. These findings indicate a substantial air pollution burden in urbanized zones, highlighting potential health risks to the local population (Figures 8 and S2). By contrast, the western and southwestern parts of Chiang Mai Province consistently exhibited lower PM_{2.5} concentrations. Specifically, districts such as Mae Chaem, Omkoi, and Galyani Vadhana showed relatively low average PM_{2.5} concentrations throughout the study period.

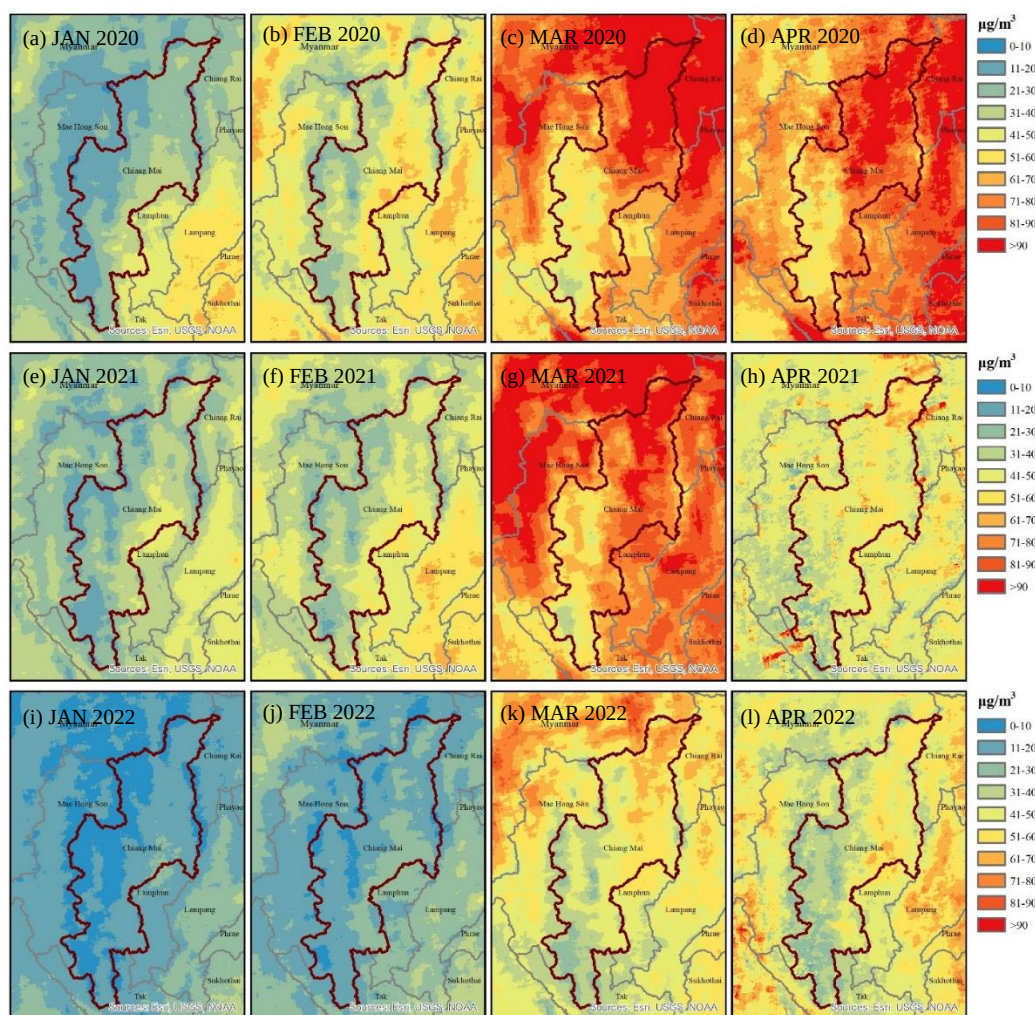


Figure 6. Monthly average satellite-derived PM_{2.5} concentrations for 2020-2022: (a) January 2020, (b) February 2020, (c) March 2020, (d) April 2020, (e) January 2021, (f) February 2021, (g) March 2021, (h) April 2021, (i) January 2022, (j) February 2022, (k) March 2022, and (l) April 2022

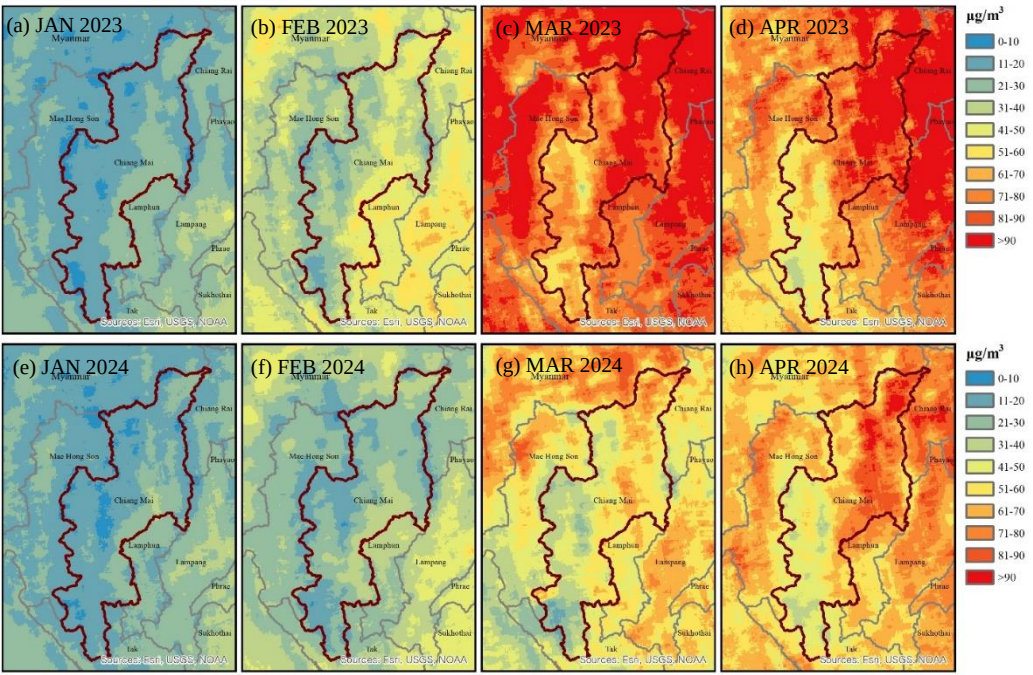


Figure 7. Monthly average satellite-derived PM2.5 concentrations for 2023 and 2024: (a) January 2023, (b) February 2023, (c) March 2023, (d) April 2023, (e) January 2024, (f) February 2024, (g) March 2024, and (h) April 2024

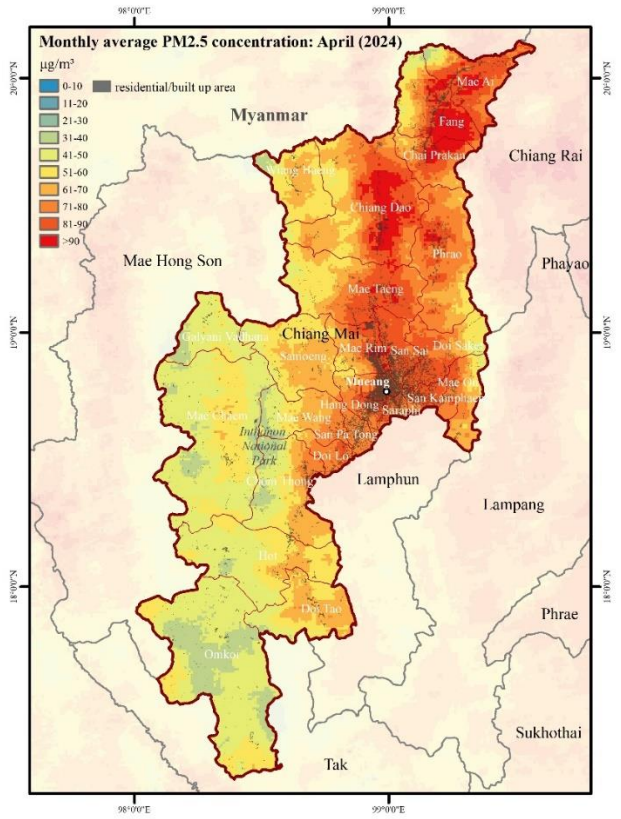


Figure 8. Overlay of average PM2.5 concentration (April 2024) on residential areas, illustrating potential population exposure during the burning season

Figure 9 presents monthly minimum, maximum, mean, and standard deviation (SD) values of satellite-derived PM2.5 concentrations during the burning period (2022-2024) in Chiang Mai. While January generally shows low air pollution levels, concentrations increase sharply by March,

highlighting the influence of seasonal biomass burning on regional air quality (Lalitaporn and Boonmee, 2019). The highest monthly mean, $79.18 \pm 16.90 \mu\text{g}/\text{m}^3$, was recorded in March 2023, whereas the lowest monthly mean, $11.12 \pm 4.18 \mu\text{g}/\text{m}^3$, was in January 2022. The maximum value, $194.81 \mu\text{g}/\text{m}^3$, was recorded in April 2021.

High SD values in March and April indicate considerable spatial and temporal variability in air pollution levels. This variation may be due to differences in local emission sources and topographical influences. For example, areas in the

southwestern area of Chiang Mai Province generally exhibit lower PM_{2.5} levels, whereas the central and northeastern regions show notably higher concentrations (Figures 6-8). Variations in meteorological conditions and emission sources may result in different adverse health effects across the province (Sapbamrer et al., 2024), requiring further investigation at provincial and regional scales. To illustrate the spatial distribution and provide a long-term overview of air pollution during the burning period, PM_{2.5} maps for 2020-2024 are presented in Figure 10.

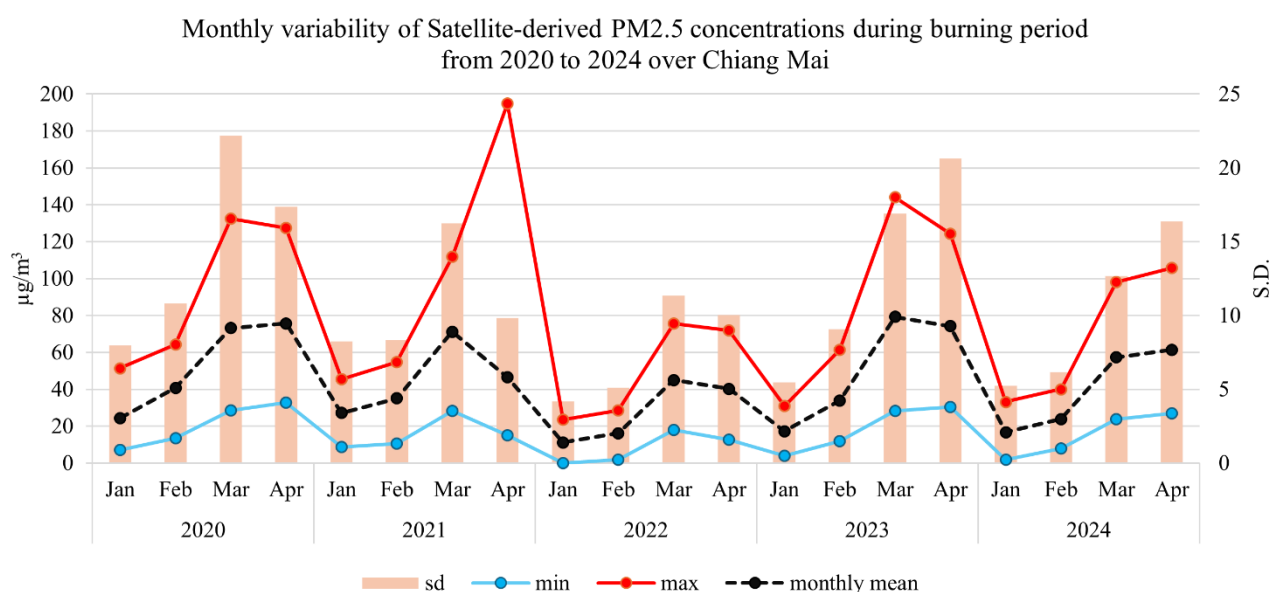


Figure 9. Descriptive statistics (minimum, maximum, mean, and standard deviation) of satellite-derived PM_{2.5} concentrations ($\mu\text{g}/\text{m}^3$) over Chiang Mai (January-April, 2020-2024)

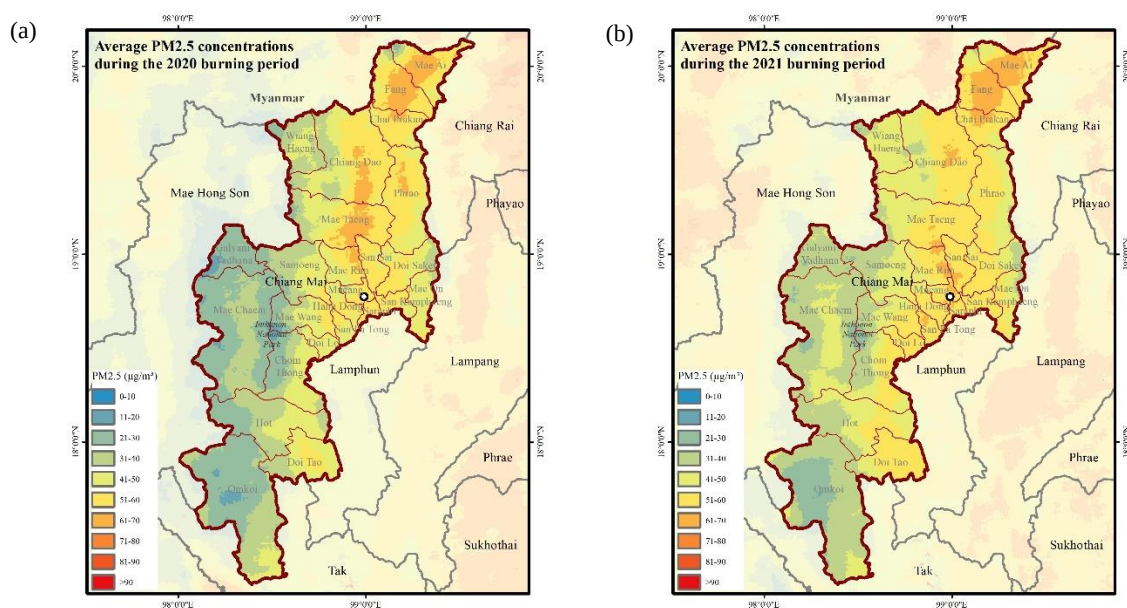


Figure 10. Average PM_{2.5} during the burning period: (a) 2020, (b) 2021, (c) 2022, (d) 2023, and (e) 2024

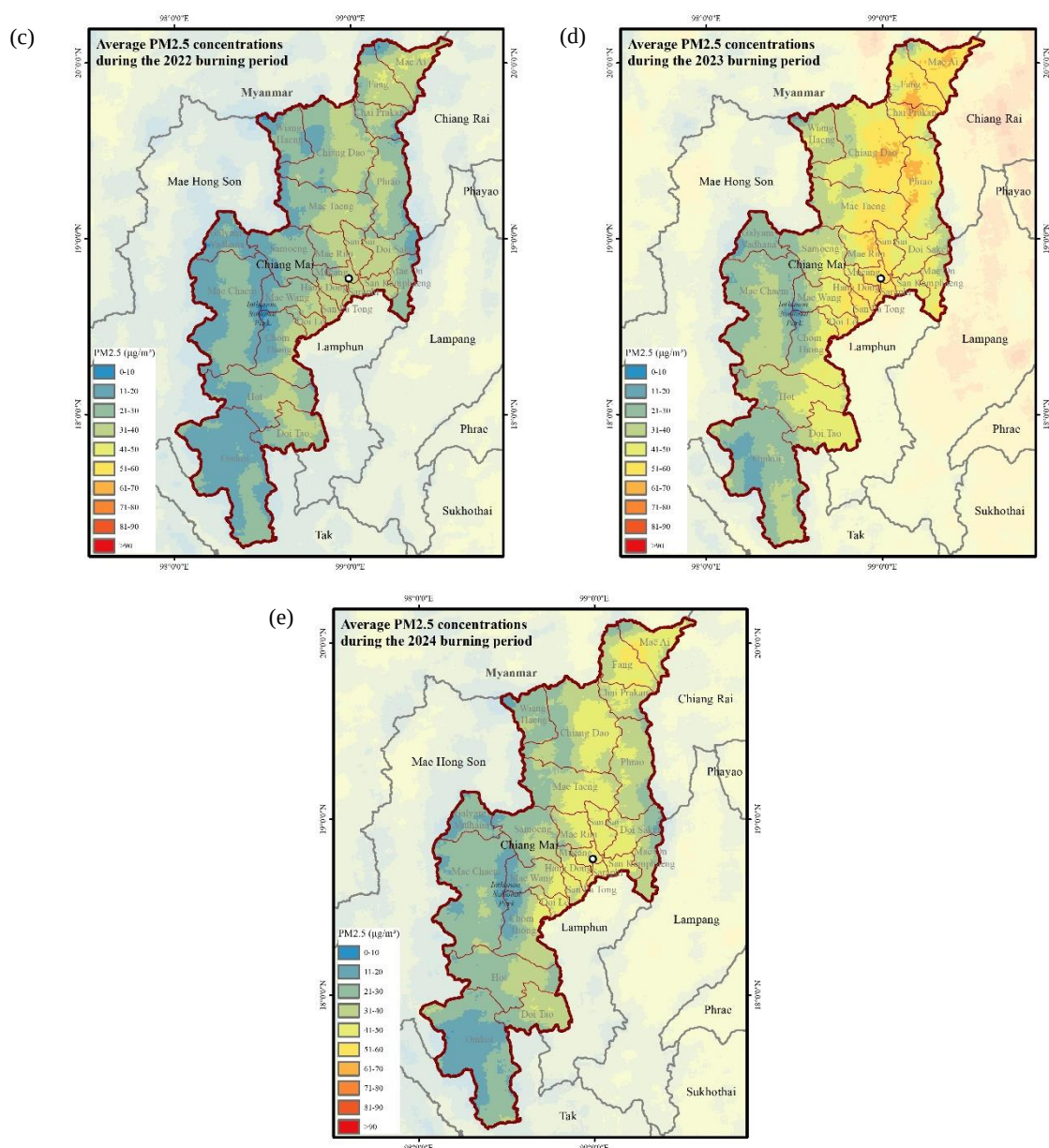


Figure 10. Average PM2.5 during the burning period: (a) 2020, (b) 2021, (c) 2022, (d) 2023, and (e) 2024 (cont.)

3.4 Policy implications and transboundary pollution challenges

The PM2.5 crisis constitutes a complex structural challenge driven by transboundary and socioeconomic factors rather than a singular seasonal event. Intense hotspots in northern border districts, such as Mae Ai, align spatially with active fires in Myanmar, consistent with [Amnuaylojaroen et al. \(2020\)](#)'s finding that westerly winds facilitate the long-range transport of biomass burning aerosols into Northern Thailand. Persistent border hotspots suggest that pollution is due to local burning and transboundary transport within a shared "airshed," where pollutants are trapped regardless of national borders. Effective management requires a dual

strategy: enforcing "haze-free" trade standards for agricultural imports to address supply-chain root causes under the ASEAN Haze Agreement and scientifically delineating the northern ASEAN airshed for joint monitoring.

To mitigate domestic emissions effectively, a holistic strategy encompassing rural agricultural management and urban traffic control is required. Initiatives like the Mae Chaem Model exemplify successful integrated resource management, with [Kamton et al. \(2019\)](#) reporting a continuous decline in forest fires, corroborated by the lower PM2.5 levels detected in this study. However, enforcement-based "zero burning" policies require re-evaluation. [Suriyawong et al. \(2023\)](#) argue that total restrictions

on burning can result in leaf-litter accumulation, leading to severe wildfires; thus, “prescribed burning” for fuel management is recommended alongside socioeconomic solutions such as agricultural carbon credit markets and high-value alternative crops. Chansuebsri et al. (2024) identified traffic emissions as the dominant source in urban contexts, contributing 76% of PM_{2.5} during the non-smoke-haze period. Consequently, policy initiatives must prioritize expanding public transportation and electric vehicles to mitigate vehicular emissions year-round.

Structurally, management frameworks should transition toward a decentralized “northern haze sandbox” model while empowering local authorities with integrated budgets. This requires a professional agency utilizing big data, such as this study’s high-resolution maps, for precise year-round planning. Finally, public health agencies must use these findings to prioritize resource allocation, including N95 masks and clean air rooms, for vulnerable populations in the unmonitored border districts identified in this study.

3.5 Limitations

While this study effectively mapped PM_{2.5} spatial distributions, it has several limitations. First, satellite data continuity is compromised by missing values, particularly during cloud cover or precipitation. Moreover, the coarse temporal resolution of satellite observations (typically one or two measurements per day) may not adequately capture the full diurnal variability of PM_{2.5} concentrations (Kaewmesri et al., 2024). This temporal sparsity can introduce inaccuracies, potentially biasing daily average estimations.

Second, the current model architecture excludes meteorological variables (e.g., wind speed, relative humidity, PBLH) for operational simplicity and to minimize dependency on external datasets. While this omission introduces uncertainty regarding aerosol hygroscopic growth and vertical dispersion, this study assumes that satellite-derived column densities (AOD, CO, NO₂) implicitly integrate these effects; for example, stagnant atmospheric conditions directly result in pollutant accumulation that is captured by the model inputs.

Third, a large performance disparity was observed between seasons. While the integration of AOD and TROPOMI data proved robust during the burning period ($R^2=0.72$), accuracy decreased markedly during the non-burning period ($R^2=0.26$). To quantify this disparity, an independent t-test on

absolute prediction errors confirmed a statistically significant difference ($t=11.19$, $p<0.001$), with a mean absolute error of $13.48 \mu\text{g}/\text{m}^3$ during the burning season, compared with $7.17 \mu\text{g}/\text{m}^3$ in the non-burning season. This reduced predictive capability, verified by statistical divergence, is likely due to weaker physical correlations between ground-level PM_{2.5} and biomass burning proxies (CO, AOD) during the wet season. Specifically, precipitation scavenging and the shift in dominant emission sources reduce the strength of the direct relationship between satellite-derived column densities and surface concentrations. Consequently, the current MLR model is not recommended for year-round operational monitoring. To address this limitation, future studies could develop season-specific models or employ nonlinear machine learning approaches to better capture variability during low-pollution periods.

Finally, validating high-resolution estimates remains a primary challenge. This study used $1 \times 1 \text{ km}^2$ MAIAC AOD to enhance spatial precision, an approach shown by Mei et al. (2019) to improve estimation accuracy. However, the validation process was constrained by the sparse distribution of ground monitoring stations, particularly the limited number of reference-grade stations within Chiang Mai. To mitigate this spatial limitation, the training dataset included stations from neighboring provinces to capture broader regional aerosol characteristics, ensuring the model learned generalized patterns. Additionally, model robustness was reinforced through temporal validation (predicting 2024 data), confirming predictive accuracy despite spatial constraints. Nevertheless, the lack of monitors in remote border areas restricts full validation of the pollution hotspots identified by the satellite model.

For future work, the recently launched GEO-KOMPSAT-2B satellite, equipped with the Geostationary Environment Monitoring Spectrometer, offers higher temporal resolution data, potentially addressing diurnal variability issues and enhancing research performance. Additionally, the authors plan to investigate the associations between PM_{2.5} and meteorological parameters (precipitation, temperature, relative humidity, wind speed, and PBLH) and socioeconomic factors to identify the drivers of PM_{2.5} in Chiang Mai. Finally, future studies could explore substituting AOD data with TROPOMI-derived data when AOD is unavailable, as Son et al. (2023) indicated that TROPOMI data alone can provide accurate estimations.

4. CONCLUSION

This study characterized the spatio-temporal variation of satellite-derived PM_{2.5} in Northern Thailand (2020-2024) by integrating TERRA-MODIS AOD with Sentinel-5P CO and NO₂ data within the GEE platform. Analysis revealed a consistent annual increase in pollution during the burning period (January-April), peaking in March. Seasonal average concentrations ranged from 25.18 µg/m³ (2022) to 51.33 µg/m³ (2020), highlighting notable inter-annual variability.

The model achieved robust performance ($r=0.88$, $R^2=0.77$, $RMSE=14.60$ µg/m³), confirming that combining gas species data (CO, NO₂) significantly enhances estimation accuracy compared with AOD-only methods. Distinct from the complex machine learning approaches increasingly used in Thailand, this study demonstrates that a physically interpretable regression framework enriched with biomass burning tracers offers competitive accuracy with simpler, cloud-based operational implementation.

Future research should incorporate meteorological (e.g., wind speed, temperature) and socioeconomic parameters to further refine model precision. Based on the identification of intense border hotspots, policymakers are recommended to prioritize installing ground monitors and allocating healthcare resources to unmonitored northern districts. Overall, this work highlights the potential of multi-source satellite integration to fill data gaps in areas with limited ground monitoring, providing a crucial baseline for assessing the health impacts of air pollution on local populations.

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AUTHOR CONTRIBUTIONS

Conceptualization, W.S. and A.C.; Methodology, W.S., A.C, P.H. and W.T.; Validation, W.S. and A.C.; Formal Analysis, W.S.; Data Curation, W.S.; Writing-Original Draft Preparation, W.S.; Writing-Review and Editing, W.S., P.H., W.T. and A.C.; Visualization, W.S.; Supervision, A.C.; Project Administration, W.S.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Assessing Eutrophication in a Small Polluted Reservoir Through Landsat 8 Band-Ratio Models: The Case of Xuan Khanh Reservoir, Hanoi, Vietnam

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ABSTRACT

This study develops an integrated framework for monitoring eutrophication in Xuan Khanh Reservoir (XKR), Hanoi, Vietnam, by combining in-situ observations with Landsat 8 (L8) reflectance data. A total of 66 field measurements collected during four surveys (October 2024-July 2025) were used to calibrate an empirical model for estimating the Trophic State Index (TSI) from L8-derived reflectance. The near-infrared to red ratio (B5/B4) achieved the best performance ($R^2=0.81$; RMSE=2.4). Nineteen cloud-free L8 images acquired between July 2021 and July 2025 were then applied to map spatiotemporal TSI variations. Results show that XKR consistently remained in a highly eutrophic to hypereutrophic state, with TSI values ranging from 64 to 82. Spatial patterns revealed persistent hotspots in shallow northern zones and inlet-connected areas, driven by external nutrient inputs and surrounding land-use pressures. These findings demonstrate the value of L8 as a cost-effective monitoring tool for small, polluted reservoirs, offering evidence to guide nutrient reduction, wastewater management, and land-use regulation. The proposed approach provides transferable insights for long-term trophic state assessment and can support policy decisions aimed at safeguarding freshwater resources in data-limited regions.

HIGHLIGHTS

A Landsat-8-based framework was applied to eutrophication monitoring in a small reservoir. An empirical NIR-to-red band-ratio model was developed to estimate the Trophic State Index (TSI). Four-year spatiotemporal variability revealed persistent eutrophic to hypereutrophic conditions and localized hotspots.

1. INTRODUCTION

Eutrophication remains one of the most consequential stressors on freshwater ecosystems, degrading water quality, ecosystem services, and human health. Small reservoirs, particularly those located in urban and peri-urban environments, are especially susceptible to eutrophication due to their limited water volume, shallow depth, restricted flushing capacity, and disproportionately high nutrient inputs (Dorgham, 2014). These characteristics result in rapid and pronounced fluctuations in algal biomass and water clarity, making eutrophication dynamics in small reservoirs both environmentally critical and

technically challenging to monitor using conventional in-situ approaches. Conventional field-based monitoring programs often suffer from sparse temporal sampling and limited spatial representativeness, which are insufficient to capture the high spatio-temporal variability characteristic of eutrophic small reservoirs. Satellite remote sensing provides a complementary solution by offering synoptic, repeatable observations over extended time periods (Batina and Krtalic, 2024). Among available satellite missions, Landsat-8/OLI (L8) remains particularly valuable due to its free access, global coverage, 30-m spatial resolution, and decade-long

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data continuity, enabling the monitoring of small reservoirs and long-term water-quality change, despite its relatively coarse 16-day revisit frequency (Olmanson et al., 2020).

The Trophic State Index (TSI) is a widely adopted framework for characterizing eutrophication by integrating key water-quality variables into a standardized 0-100 scale. Among its components, chlorophyll-a concentration (Chla) and Secchi disk depth (SDD) are directly linked to the optical properties of surface water and can therefore be reliably estimated from satellite-derived reflectance. Consequently, TSI, particularly TSI (Chla) and TSI (SDD), has been widely applied in remote sensing-based assessments of lake and reservoir trophic status. Numerous studies have demonstrated robust relationships between Landsat-derived reflectance and SDD (Lee et al., 2016; Liu et al., 2020; Song et al., 2022) or Chla (Karimi et al., 2024; Vinh et al., 2019; Yadav et al., 2019), enabling the estimation of TSI across diverse aquatic environments (Hu et al., 2022; Li et al., 2022; Lyu et al., 2022; Vinh et al., 2022).

A growing body of research has confirmed the feasibility of Landsat-8 for monitoring eutrophication through empirical band-ratio models, with reported coefficients of determination (R^2) typically ranging from 0.57 to 0.75 (e.g., Watanabe et al., 2015; Hu et al., 2021; Zhou et al., 2019; Vinh et al., 2022; Kiwanuka et al., 2025a). However, most existing studies have primarily focused on large lakes and reservoirs, where optical conditions are relatively stable and spatial resolution constraints are less pronounced (Hu et al., 2022; Li et al., 2022; Lyu et al., 2022). Consequently, the applicability and robustness of Landsat-based approaches for small, optically complex reservoirs remain insufficiently explored. In such systems, reliable satellite-based monitoring is further challenged by a combination of physical, optical, and anthropogenic factors.

Narrow water bodies are particularly susceptible to atmospheric correction uncertainties and adjacency effects, whereby reflectance signals are contaminated by surrounding land surfaces (Ogilvie et al., 2018). High turbidity, elevated suspended sediment concentrations, and shallow bathymetry further complicate optical conditions, often weakening the relationship between surface reflectance and key water-quality variables such as Chla or SDD (Palmer et al., 2015). Moreover, untreated or partially treated wastewater inputs, characterized by elevated nitrogen and phosphorus loads and increased organic matter,

can intensify algal growth and accelerate eutrophication processes, leading to pronounced spatial heterogeneity and temporal variability (Di Francesco et al., 2022; Owusu et al., 2022). These factors, when combined with frequent cloud cover in tropical regions, pose significant challenges for reliable Landsat-based eutrophication monitoring in small reservoirs (Keith et al., 2018). Despite their heightened ecological vulnerability and socio-economic importance as sources of water supply, aquaculture, and recreation, small eutrophic reservoirs remain underrepresented in remote sensing-based eutrophication studies (Di Francesco et al., 2022; Owusu et al., 2022). This underrepresentation limits the availability of timely and spatially explicit information required to support effective management and mitigation strategies at the local scale.

The distinguishing contribution of this study lies in its targeted evaluation of established Landsat-8 band-ratio models for eutrophication monitoring in a small, optically complex reservoir. Rather than proposing new spectral indices, this study systematically assesses the applicability, robustness, and limitations of commonly used band-ratio approaches when applied to a spatially constrained and highly eutrophic waters. Specifically, this study aims to: (1) develop an empirical model for estimating TSI values from L8-derived remote sensing reflectances; (2) apply the model to a time series of L8 images acquired between July 2021 and July 2025 to characterize the spatial and temporal dynamics of eutrophication; and (3) examine the relationship between the observed trophic conditions and surrounding land use patterns within the reservoir catchment. By focusing on a small-reservoir context, this study provides methodological insights and practical guidance for cost-effective eutrophication monitoring and management of vulnerable freshwater resources.

2. METHODOLOGY

2.1 Study area

XKR is an artificial freshwater body in Son Tay Town, Hanoi, Vietnam, constructed in 1964 for irrigation and aquaculture (Figure 1). It covers approximately 60 ha with an average depth of 2-4 m and is strongly influenced by the regional monsoonal climate, with inflows dominated by agricultural runoff and small tributaries. The reservoir water level is primarily regulated by local management, often maintained at relatively low levels during the

summer to accommodate heavy rainfall and reduce flood risk, and raised toward the end of the year (November-December) to store water for the subsequent winter-spring agricultural season. This

direct land-water connection makes the reservoir highly sensitive to nutrient and sediment loading from surrounding land-use.

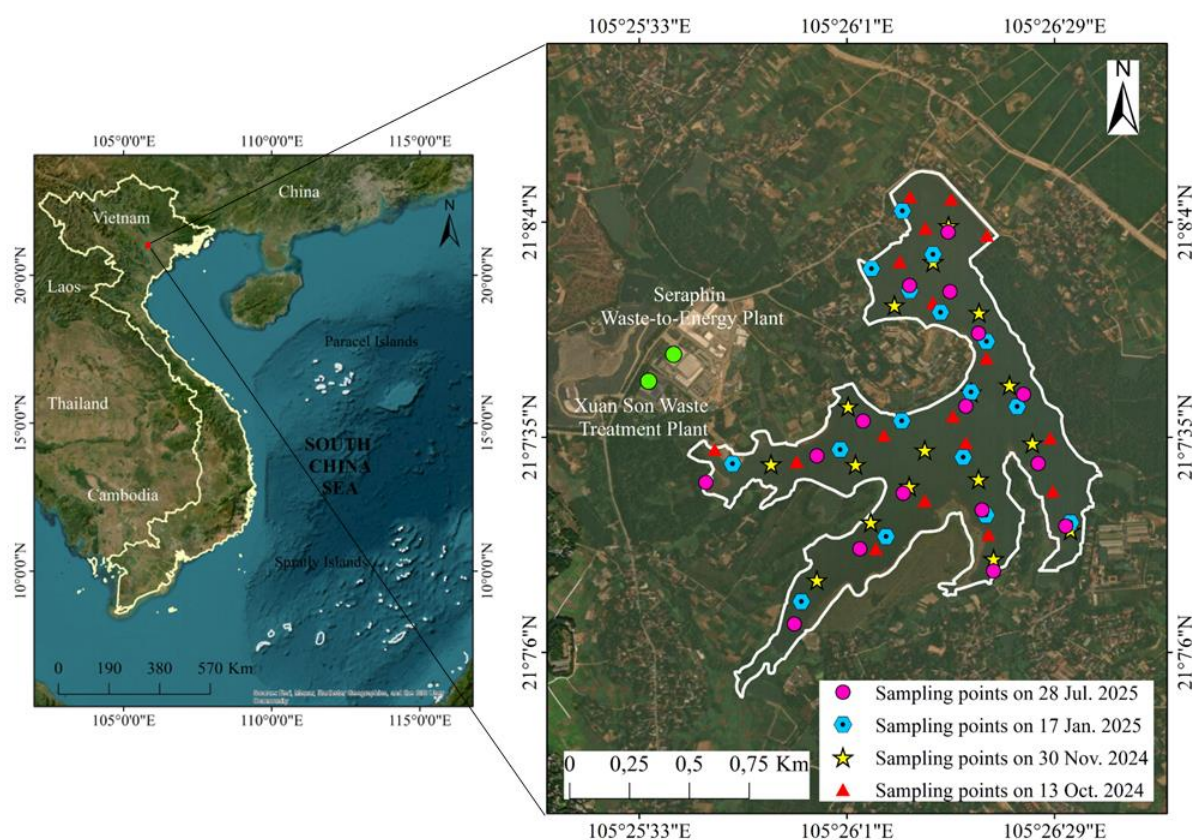


Figure 1. Locations of Xuan Khanh Reservoir in Vietnam and distribution of sampling points.

Over decades of use, the reservoir has shown increasing signs of eutrophication, including high turbidity, recurrent algal blooms, organic enrichment, and sediment accumulation (Gusev et al., 2021; Tran et al., 2021). Its proximity to the Xuan Son Waste Treatment Complex further raises concerns about nutrient and contaminant influxes from wastewater leakage (The Kha, 2018; Nguyen Hoai, 2019). In addition, the reservoir has been identified as a potential habitat for *Rafetus swinhoei*, the critically endangered Hoàn Kiếm Turtle (Bettelheim, 2012), underscoring its global biodiversity significance (Seimon et al., 2024). The combination of ecological importance and exposure to multiple anthropogenic pressures, particularly untreated or partially treated wastewater inputs rich in nutrients and organic matter, highlights the urgent need for frequent eutrophication monitoring. Despite these pressures, no systematic assessment of its trophic status has been conducted, leaving a critical gap for management and conservation. Given its ecological vulnerability and

socio-economic importance, XKR provides a representative case study for evaluating the feasibility of using L8 to monitor eutrophication through TSI estimation and mapping.

2.2 Water sampling and measurement

Field surveys at XKR were conducted on four occasions: 13 October 2024, 30 November 2024, 17 January 2025, and 28 July 2025. These campaigns were scheduled to coincide with L8 overpasses during periods of minimal cloud cover, ensuring that in-situ measurements could be directly matched with satellite observations. To enhance temporal consistency, sampling was carried out within approximately one hour before or after the satellite overpass. In total, 66 surface water samples were collected across the campaigns. Sampling points were systematically distributed throughout the reservoir (Figure 1) to represent spatial variability in water quality (Karabork, 2010). At each location, the geographic position was recorded with a handheld GPS, water

transparency (SDD) was measured using a Secchi disk, and surface water was collected for laboratory analysis.

Samples were taken from the upper 0-30 cm of the water column, representing the photic zone where phytoplankton dynamics and external nutrient inputs exert the strongest influence. Chla concentrations were analyzed following the Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Accordingly, water samples were filtered through Whatman 7184-004 cellulose nitrate membrane filters (pore size 0.45 µm; diameter 47 mm) to retain phytoplankton. The material on the filters was extracted in 90% acetone to release pigments. Chla concentrations in the extracts were then determined spectrophotometrically using a DR 6000 UV-VIS spectrophotometer (Hach, USA; spectral bandwidth 1 nm) with matched 25.4 mm cuvettes. The Chla concentration in water samples was calculated as:

$$\text{Chla } (\mu\text{g/L}) = \frac{C_a \times V_1}{V_0} \quad (1)$$

Where; V_1 is the extract volume (L), V_0 is the sample volume (m^3), and C_a is the concentration of Chla in the extract, determined by:

$$C_a = 11.85 \times D_{664} - 1.54 \times D_{647} - 0.08 \times D_{630} \quad (2)$$

Where; D_{630} , D_{647} , D_{664} are the optical densities measured at wavelengths of 630 nm, 647 nm, and 664 nm, respectively.

2.3 TSI calculation and model development

The trophic status of each sampling site was evaluated using Carlson's TSI, calculated from in-situ Chla and SDD. This approach follows the method originally proposed by Carlson (1977) and later refined by Carlson and Simpson (1996). According to this classification, a lake is considered oligotrophic when mean TSI values are <30, mesotrophic when 30-50, slightly eutrophic at 50-60, highly eutrophic at 60-70, and hypereutrophic when values exceed 70 (typically approaching 100). The TSI value at each sampling point was determined using the following equations:

$$\text{TSI} = \frac{\text{TSI}(\text{Chla}) + \text{TSI}(\text{SDD})}{2} \quad (3)$$

$$\text{TSI}(\text{Chla}) = 9.81 \cdot \ln(\text{Chla}) + 30.6 \quad (4)$$

$$\text{TSI}(\text{SDD}) = 60 - 14.41 \cdot \ln(\text{SDD}) \quad (5)$$

Where; Chla is expressed in µg/L and SDD in meters. All TSI values are unitless.

To extend this approach using remote sensing, we developed an empirical model for estimating TSI from L8 imagery. First, correlations between in-situ TSI values and L8-derived spectral reflectance at corresponding sampling points were examined to identify effective band ratios or combinations. Model calibration was performed using 50 paired observations collected during three campaigns (13 October 2024, 30 November 2024, and 17 January 2025). An independent dataset of 16 samples from 28 July 2025 was used for validation, allowing assessment of model transferability across different seasonal and trophic conditions.

A set of linear and non-linear regression models was constructed to characterize the relationships between selected band indices and TSI. The optimal model was selected based on statistical performance indicators, including Pearson's correlation coefficient (r), coefficient of determination (R^2), and root mean square error (RMSE), evaluated for both calibration and validation datasets at a significance level of $p < 0.05$. The validated model was then applied to a time series of 19 L8 images acquired between July 2021 and July 2025 to generate spatially explicit maps of seasonal and interannual TSI variability in XKR.

2.4 L8 image processing and mapping method

A total of 19 L8 scenes (path 127, row 45) covering Hanoi, Vietnam, were obtained from the USGS Earth Explorer portal (<https://earthexplorer.usgs.gov/>). Details of the selected images are provided in Table 1. All scenes correspond to Level-2A products, which provide atmospherically corrected surface reflectance generated using the Land Surface Reflectance Code (LaSRC) algorithm (Vermote et al., 2016). The use of LaSRC-based reflectance (hereafter L8-LaSRC) was motivated by its demonstrated reliability for inland water quality monitoring (Bernardo et al., 2017; Pham et al., 2018; Allam et al., 2020; Vinh et al., 2022), combined with its accessibility and computational efficiency.

Accordingly, all L8-LaSRC images were inspected for cloud contamination, and only cloud-free or minimally cloudy scenes were retained (Table 1). The Modified Normalized Difference Water Index (MNDWI) was then applied to delineate water bodies and mask out land areas (Xu, 2006). This step

ensured that only pure water pixels within the reservoir were included in the analysis.

For calibration purposes, spectral reflectance values corresponding to in-situ sampling locations were extracted using ENVI 5.3. Four field-validated

images, coinciding with the water sampling campaigns, were used to establish relationships between L8 band ratios/indices and TSI values. These relationships were used to calibrate empirical regression models.

Table 1. List of L8 scenes used for mapping, calibration, and validation of TSI in XKR

Purpose	Landsat product identifier (Path 127/Row 45)	Acquisition date	Notes
Mapping	LC08_L2SP_127045_20210717_20210729_02_T1	17/07/2021 - 22/03/2025	Used to produce time-series TSI maps
	LC08_L2SP_127045_20210818_20210827_02_T1		
	LC08_L2SP_127045_20211005_20211013_02_T1		
	LC08_L2SP_127045_20220704_20220707_02_T1		
	LC08_L2SP_127045_20220906_20220914_02_T1		
	LC08_L2SP_127045_20221024_20221101_02_T1		
	LC08_L2SP_127045_20221109_20221121_02_T1		
	LC08_L2SP_127045_20230504_20230509_02_T1		
	LC08_L2SP_127045_20230707_20230718_02_T1		
	LC08_L2SP_127045_20231027_20231101_02_T1		
	LC08_L2SP_127045_20231128_20231208_02_T1		
	LC08_L2SP_127045_20231214_20240102_02_T1		
	LC08_L2SP_127045_20240420_20240429_02_T1		
	LC08_L2SP_127045_20240810_20240815_02_T1		
	LC08_L2SP_127045_20250322_20250327_02_T1		
Calibration	LC08_L2SP_127045_20241013_20241021_02_T1	13/10/2024, 30/11/2024, 17/01/2025	Matched with in-situ measurements for model calibration
	LC08_L2SP_127045_20241130_20241203_02_T1		
	LC08_L2SP_127045_20250117_20250127_02_T1		
Validation	LC08_L2SP_127045_20250728_20250807_02_T1	28/07/2025	Independent dataset for model validation

Then, the optimal regression model was applied to all 19 cloud-free L8 images acquired between July 2021 and July 2025 to estimate TSI across the reservoir. Pixel-level TSI values were computed and aggregated into thematic maps, allowing the visualization of eutrophication patterns. The results were classified into 18 Jenks classes to highlight spatial gradients of trophic status and to adequately represent the high spatial variability within this small reservoir.

Finally, in addition to spatial mapping, estimated TSI values from the 19 scenes were analyzed to identify seasonal and interannual variations. This approach provided insights into both the temporal dynamics of eutrophication and the influence of hydrological seasonality and external inputs. The overall workflow, from in-situ data collection and model calibration to the mapping of TSI distribution from L8 imagery, is summarized in [Figure 2](#).

3. RESULTS

3.1 Water quality and trophic status of Xuan Khanh Reservoir

[Figure 3](#) shows temporal variations in Chla, SDD, and TSI in XKR across four sampling periods (October 2024, November 2024, January 2025, and July 2025). Accordingly, Chla in the reservoir water displayed pronounced seasonal fluctuations. The highest levels were observed in October 2024, with a mean of ~108 µg/L and extreme values exceeding 180 µg/L, indicating severe algal proliferation at the onset of autumn. Concentrations declined sharply by late November (~57 µg/L), accompanied by reduced variability, suggesting a temporary reduction in algal biomass. The lowest mean values were recorded in January 2025 (~40 µg/L), although variability was wide (27-88 µg/L), pointing to spatially heterogeneous conditions during winter. By July 2025, Chla increased again (mean ~65 µg/L), reflecting moderate

but persistent algal activity during the summer. This seasonal cycle highlights a typical pattern of autumn

algal blooms, winter decline, and summer resurgence linked to nutrient dynamics and stratification.

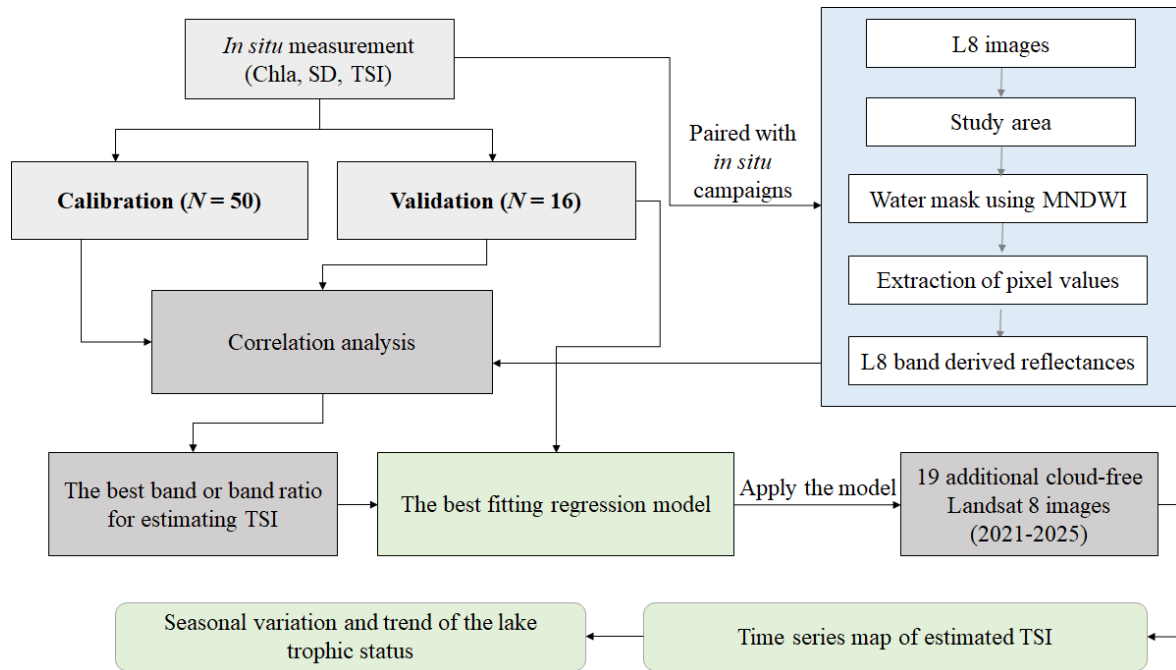


Figure 2. Workflow for estimating and mapping the Trophic State Index (TSI) in XKR using Landsat 8 imagery, integrating in-situ data, model calibration/validation, and time-series analysis. MNDWI refers to the Modified Normalized Difference Water Index.

Consistent with these patterns, SDD showed an inverse response to seasonal changes in Chla, confirming the inverse relationship between algal biomass and water clarity. Across all sampling campaigns, Chla was negatively correlated with SDD ($r=-0.85$, $p<0.01$), confirming that phytoplankton biomass is the dominant driver of transparency in the reservoir. This negative relationship reflects the typical eutrophic condition, where elevated algal growth consistently reduces light penetration. SDD was poorest in October 2024 (mean ~ 0.33 m), coinciding with the peak bloom, and improved markedly by November (~ 0.67 m) and January (~ 0.73 m), when algal concentrations were lower. In July 2025, SDD declined again (~ 0.43 m), reflecting reduced clarity due to renewed algal growth and possibly higher suspended solids during the wet season.

The trophic state of the reservoir, expressed as TSI, remained consistently in the eutrophic to hypereutrophic range across all four surveys. Both TSI (Chla) and TSI (SDD) were highest in October 2024 (means ~ 73 -75), clearly above the hypereutrophic threshold (>70). Although lower in November and January (means ~ 66 -69), values still indicated eutrophic to highly eutrophic conditions. By July

2025, TSI values increased again (~ 72), reflecting renewed eutrophication pressure during midsummer. These results demonstrate that XKR is persistently eutrophic, with episodic shifts into hypereutrophic conditions, driven largely by algal blooms and fluctuating transparency.

Based on the field datasets collected during the four surveys shown in Figure 3, the measurements from 13 October 2024, 30 November 2024, and 17 January 2025 exhibited wide ranges of Chla, SDD, and TSI values, making them appropriate for constructing the calibration dataset. In contrast, the dataset from 28 July 2025 displayed a narrower distribution of these parameters and was therefore used as an independent dataset to verify model performance under a different seasonal context with distinct climatic characteristics.

3.2 Model to estimate the Trophic State Index (TSI)

Figure 4 shows L8 band-based remote sensing reflectance spectra, $L8\text{-}LaSRC R_{rs}(\lambda)$, derived from 66 sampling points, representing two contrasting hydrological seasons (wet and dry). Clear temporal differences in optical properties were observed across the seven spectral bands. In October, water reflectance was consistently higher, particularly in the green (B3) and near-infrared (B5) bands, indicating elevated

turbidity or suspended particulate matter during the wet season. By contrast, spectra from November and January displayed lower and more uniform reflectance across all bands, consistent with clearer water and reduced phytoplankton biomass. These seasonal differences align with earlier findings that water reflectance increases during periods of algal proliferation or high nutrient loading (Wang et al., 2025; Kiwanuka et al., 2025b). The reduced variability and subdued reflectance in the cooler, drier months

further support the interpretation of enhanced water clarity when algal growth is constrained by lower temperatures and nutrient availability. Unlike the L8 band-based spectra typically observed in marine and coastal waters (Yan et al., 2023), the L8-LaSRC $R_{rs}(\lambda)$ spectra of XKR water show a distinct peak in the near-infrared band (B5), indicative of high phytoplankton biomass and suspended matter in the water column, as also reported by Ha et al. (2022) and Ha et al. (2024).

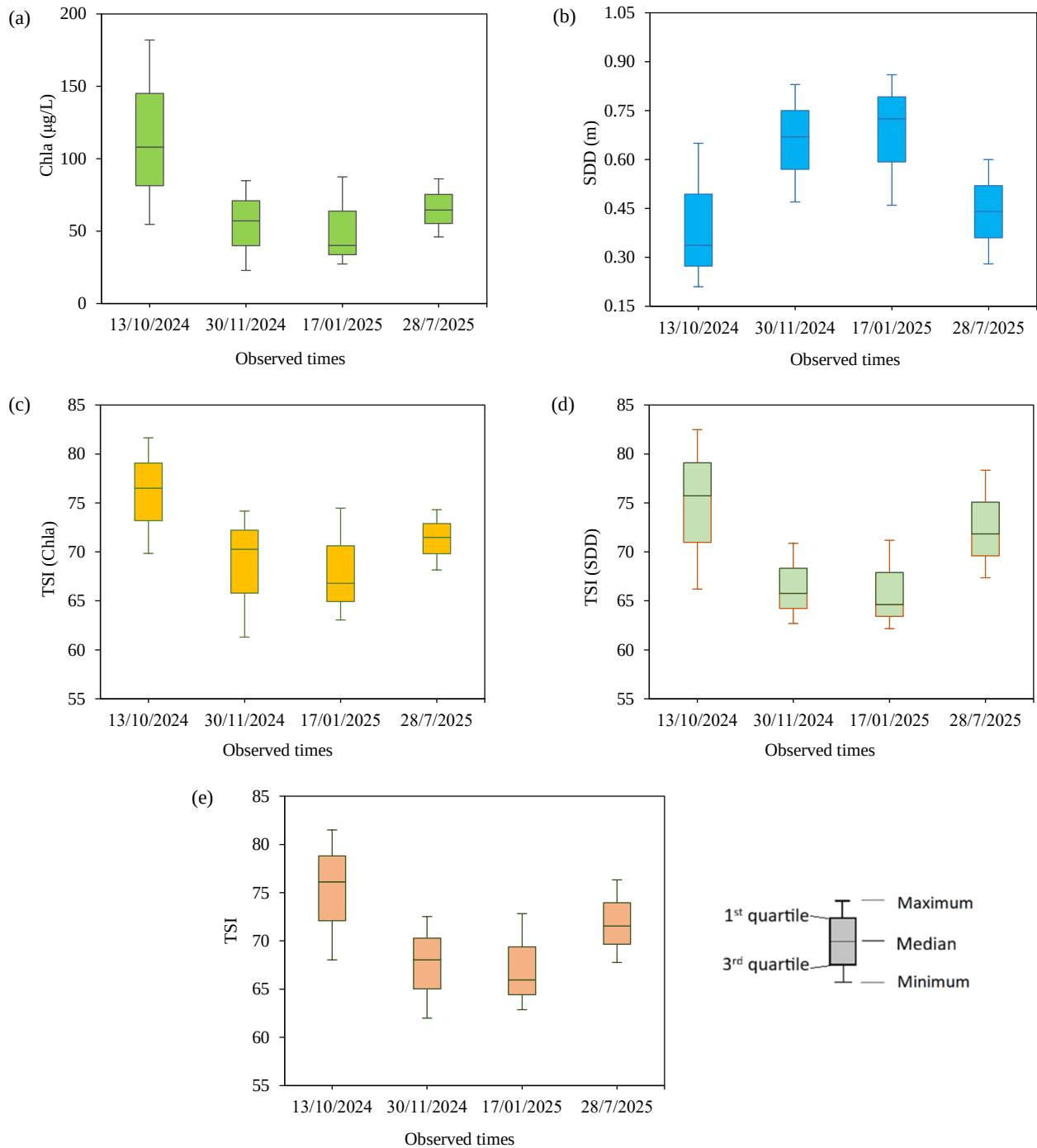


Figure 3. Temporal variations of chlorophyll-a (Chla) (a), Secchi disk depth (SDD) (b), TSI(Chla) (c), TSI(SDD) (d), and overall TSI (e) in XKR based on four field campaigns (13 October 2024, 30 November 2024, 17 January 2025, and 28 July 2025).

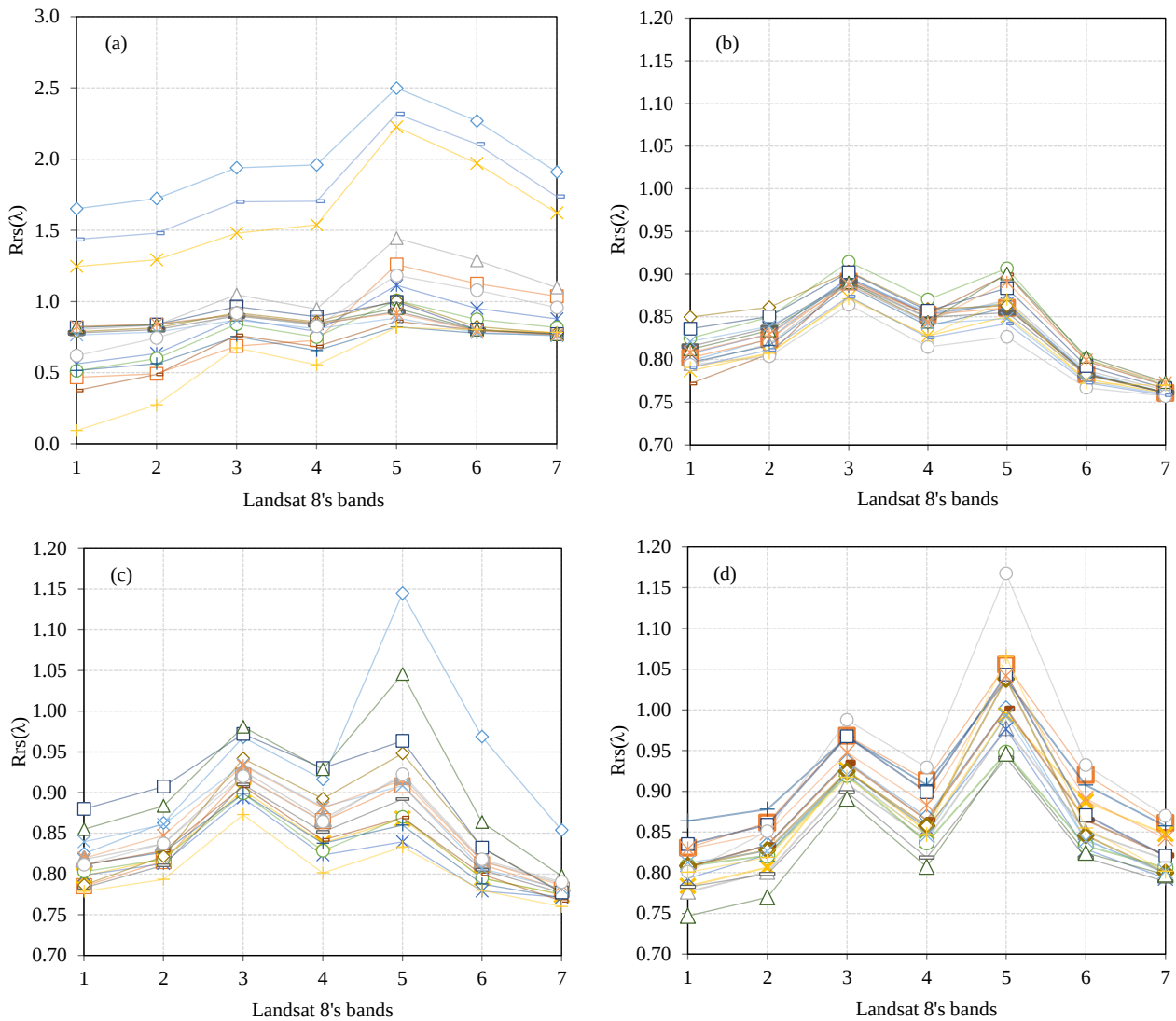


Figure 4. The Landsat 8 band-based reflectance spectra of water at sampling points were obtained on the following dates: a) October 13, 2024 (N=17); b) November 30, 2024 (N=17); c) January 17, 2025 (N=16) and d) July 28, 2025 (N=16). The bands are labeled as B1 to B7 corresponding to band 1 to band 7 of the Landsat 8 imagery.

Figure 5(a) illustrates the correlations between Chla, SDD, and Landsat-8 single bands and band ratios using data from all four campaigns. Chla exhibits consistently positive correlations with band ratios involving the red-edge and red bands, particularly B5/B4 ($r=0.89$) and B5/B3 ($r=0.85$), indicating sensitivity to phytoplankton-related scattering and absorption features. In contrast, SDD shows strong negative correlations with several band ratios, reflecting the inverse relationship between water transparency and optically active constituents. These results indicate that band-ratio combinations tend to provide stronger and more consistent relationships than single bands. The relationships between in-situ TSI and L8-LaSRC $R_{rs}(\lambda)$ values were also investigated (Figure 5(b)). Overall, TSI showed weak and inconsistent correlations with individual

spectral bands, with the exception of January, when stronger relationships emerged ($r=0.81$ for B6; $r=0.78$ for B5). This suggests that the shortwave infrared (B6) and near-infrared (B5) regions are more sensitive to trophic variations under cooler, clearer-water conditions. In contrast, October and November datasets yielded weaker correlations, particularly in the visible range (B1-B4), likely due to high turbidity masking algal signals. When all seasons were pooled, only moderate correlations were observed in B5 ($r=0.54$) and B6 ($r=0.51$), indicating that no single band consistently captured TSI dynamics. These results demonstrate that single-band approaches are inadequate for XKR, and that multi-band or band-ratio algorithms are more appropriate for estimating TSI under variable optical conditions.

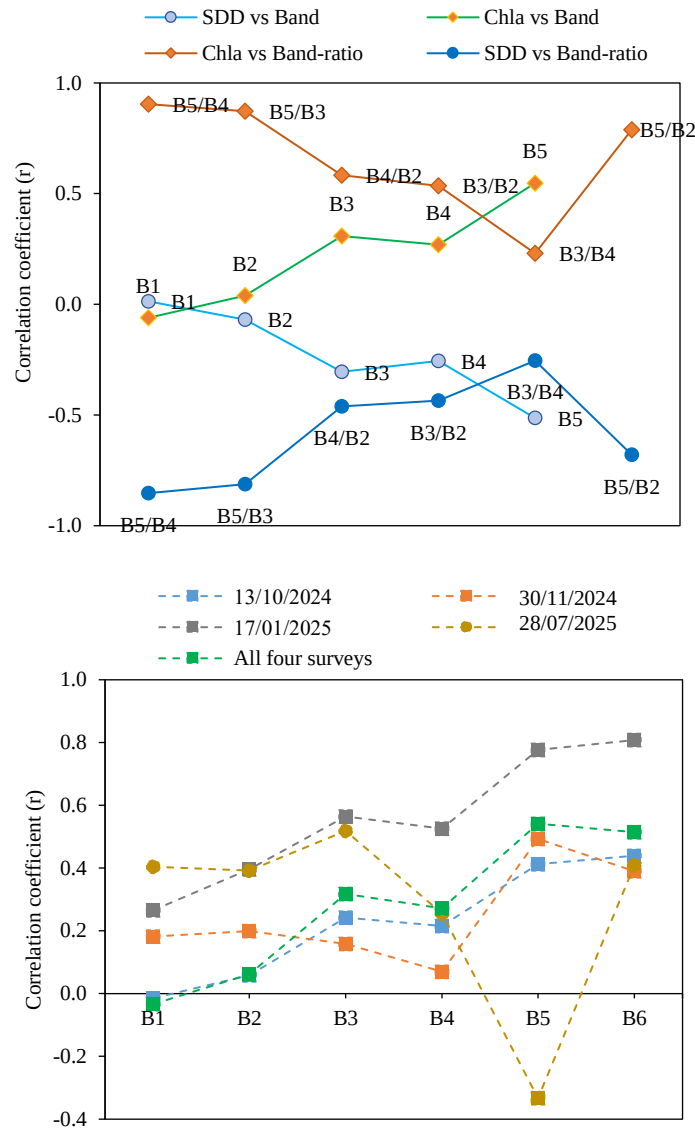


Figure 5. The correlations between Chla and SDD with Landsat 8 bands and band-ratios using data from all four campaigns (a), and between TSI with Landsat 8 bands (b)

Six L8 band ratios were tested against in-situ TSI values (Figure 6). Among the models evaluated, exponential regressions generally produced lower errors than linear or logarithmic fits, consistent with previous findings on trophic state modeling (Ha and Koike, 2011). The NIR-to-red ratio (B5/B4) showed the strongest performance ($R^2=0.80$, $RMSE=0.04$), followed closely by the NIR-to-green ratio (B5/B3; $R^2=0.73$, $RMSE=0.04$). Both indices highlight the effectiveness of NIR-involved ratios in capturing chlorophyll-related signals. In contrast, the green-to-red (B3/B4) and green-to-blue ratios (B3/B1, B3/B2) yielded weak to moderate correlations ($R^2 \leq 0.27$), indicating limited predictive value in this dataset. The blue-to-NIR ratio (B2/B4) displayed a moderate

negative relationship with TSI ($R^2=0.44$). Overall, these results confirm that band ratios incorporating NIR bands, particularly B5/B4, are the most suitable for estimating trophic status in XKR.

Accordingly, the NIR-to-red ratio (B5/B4) was identified as the most effective predictor of TSI in XKR. An exponential regression model was fitted to describe the relationship, which is expressed as:

$$TSI = 40.8 \times e^{0.48 \frac{B5}{B4}} \quad (6)$$

Where; B5 and B4 represent the remote sensing reflectance $R_{rs}(\lambda)$ from the NIR and red bands of L8-LaSRC, respectively.

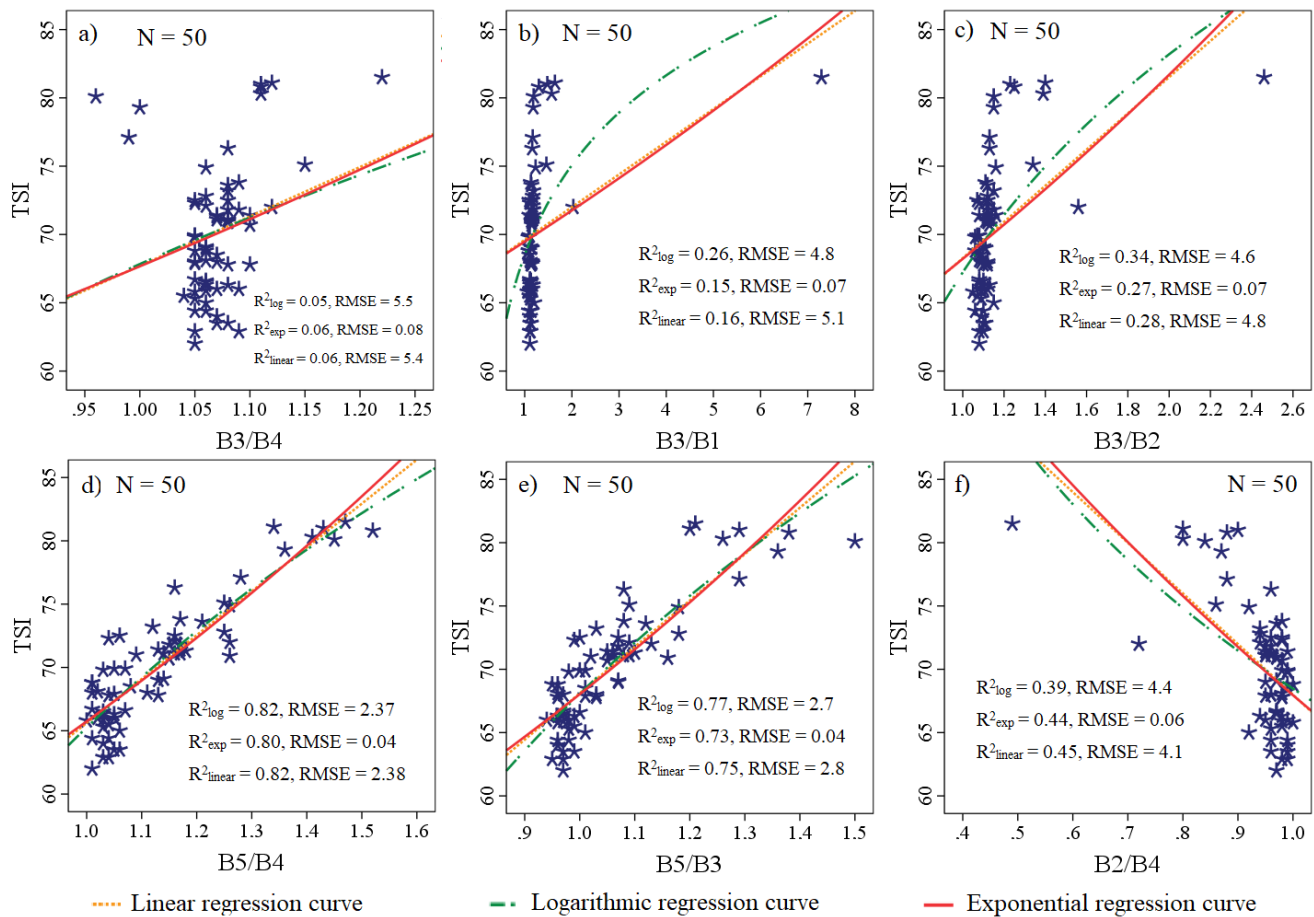


Figure 6. Cross-relationships of in-situ TSI and L8-LaSRC band ratio-based reflectances as commonly used to estimate TSI in the reviewed literature: a) green-to-red band ratio; b-c) green-to-blue band ratios; d) NIR-to-red band ratio; e) NIR-to-green band ratio; and f) blue-to-NIR band ratio. Abbreviations of the L8-LaSRC band 1 to band 5 corresponded to B1 to B5.

Model performance was evaluated using both calibration ($N=50$) and independent validation ($N=16$) datasets, which together encompassed a wide range of measured TSI values. The results demonstrated strong predictive ability, with calibration yielding $R^2=0.81$ and $RMSE=2.4$, and validation producing $R^2=0.63$ and $RMSE=1.6$ (Figure 7). The lower validation R^2 likely reflects increased temporal variability in water quality conditions across sampling campaigns, combined with the limited size of the independent validation dataset. When the datasets were combined ($N=66$), the overall performance was robust, achieving $R^2=0.81$ and $RMSE=2.2$, corresponding to only $\sim 2.5\%$ of the mean in-situ TSI. These results confirm the reliability and robustness of the proposed model for quantifying trophic status in XKR under varying seasonal and trophic conditions.

3.3 Spatial-temporal distribution of the trophic state index

Equation (6) was applied to 19 L8-LaSRC images acquired between July 2021 and July 2025 to

investigate spatial and seasonal variations in TSI across XKR. As shown in Figure 8, TSI values ranged from 64.1 (18 August 2021) to 82.0 (20 April 2024), with mean values spanning 65.1 to 75.1 over the study period, and peak TSI values consistently occurring during bloom-prone months in summer (July–September) and early spring (April). According to the trophic classification of Carlson and Simpson (1996), the reservoir consistently remained in a highly eutrophic to hypereutrophic state, with pronounced seasonal fluctuations.

Spatial patterns revealed marked heterogeneity across different parts of the reservoir. The shallow northern and northeastern zones persistently exhibited elevated TSI values, particularly during bloom-prone months, likely reflecting restricted circulation and nutrient accumulation. By contrast, the deeper central and southern zones generally maintained lower TSI, indicative of greater mixing and dilution capacity. Episodic hotspots of hypereutrophy ($TSI > 74$) were detected, especially in July 2022, April 2024, and July 2025, with peak values concentrated near inflow areas

where external nutrient inputs are greatest. Notably, in April 2024, large portions of the northern basin reached TSI values up to 78, signaling severe eutrophication and potential harmful algal bloom development. These findings suggest that eutrophication in XKR is spatially heterogeneous, with localized hotspots driven by hydrological inputs and basin morphology rather than uniform reservoir-wide processes.

Figure 9 shows temporal fluctuations in the trophic status of XKR from July 2021 to July 2025. TSI values ranged between ~64 and 82, with most observations concentrated near the eutrophic-hypereutrophic threshold (TSI~70). This indicates that the reservoir consistently shifted between highly eutrophic and hypereutrophic conditions, with strong seasonal variability. Peaks in TSI were recorded during the summers of 2022, 2024, and 2025, when values exceeded 74, reflecting intensified phytoplankton growth under warm and stratified conditions. By contrast, lower TSI values were

observed in late 2021, mid-2023, and early 2025, suggesting temporary reductions in trophic status.

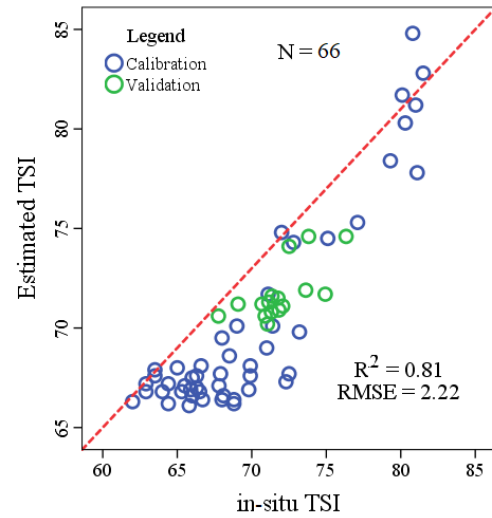


Figure 7. Relationships between in-situ and estimated TSI for both model calibration ($N=66$; $R^2=0.81$; $RMSE=2.4$) and validation ($N=16$; $R^2=0.63$; $RMSE=1.6$) datasets by the Equation (6)

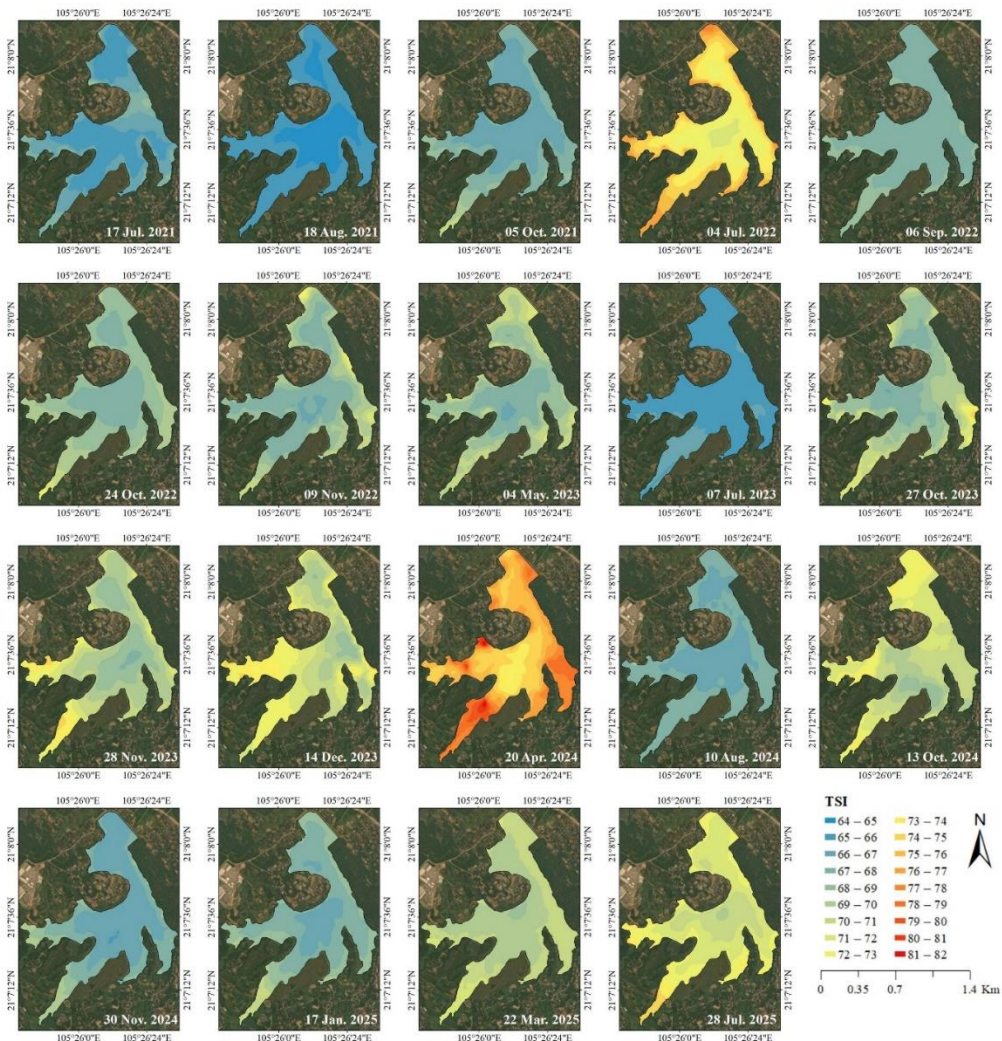


Figure 8. Spatial distribution of TSI in XKR estimated from 19 L8-LaSRC scenes acquired from July 2021 to July 2025.

Spatial heterogeneity was also evident, with boxplot ranges varying considerably between sampling times. Wider ranges, such as those in September 2022 and August 2024, indicate localized algal blooms or uneven nutrient loading across the reservoir. Interannual variability was particularly clear in July: values in 2021 were relatively low (TSI=66),

increased sharply in 2022 (TSI ~75), declined slightly in 2023 (TSI=68), and rose again in 2025, when values consistently exceeded the hypereutrophic threshold. Overall, these results demonstrate both the seasonal and interannual instability of trophic conditions in XKR.

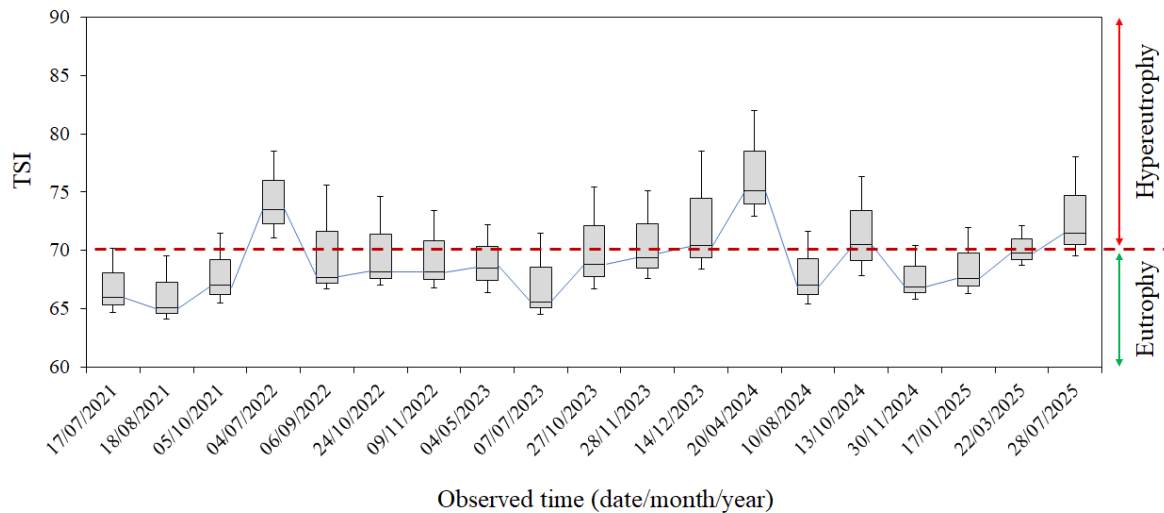


Figure 9. Temporal variations of TSI obtained from 19 L8-LaSRC images

4. DISCUSSION

Our results demonstrate that freely available L8 imagery provides a practical and reliable tool for monitoring eutrophication in small, polluted reservoirs. Despite the relatively coarse 30-m resolution, the calibrated B5/B4 model produced strong agreement with in-situ TSI, showing that Landsat data can capture both seasonal variation and spatial heterogeneity in trophic conditions. This is particularly relevant for reservoirs such as XKR, where continuous field monitoring is limited but management decisions require frequent information.

The strong performance of the NIR-to-red ratio (B5/B4) in this study confirms its suitability for monitoring eutrophication in small, algae-rich reservoirs. Previous research has demonstrated the robustness of this index for estimating Chla in turbid and productive freshwater systems using L8 imagery (Watanabe et al., 2015; Boucher et al., 2018; Markogianni et al., 2018; Lai et al., 2021), and our findings extend its applicability to XKR. Here, Chla was found to be the principal driver of trophic conditions, with TSI showing an exceptionally strong correlation with Chla ($r=0.95$). This direct linkage explains why the B5/B4 ratio, which is highly sensitive to Chla dynamics, also performs well in

estimating TSI in the reservoir. The effectiveness of B5/B4 arises from the pronounced absorption of Chla in the red band and the elevated reflectance of phytoplankton in the NIR region, which together enhance sensitivity to algal biomass. Moreover, the index is comparatively less influenced by suspended sediments than blue- or green-based ratios, which are more susceptible to scattering by non-algal particles. This makes the NIR-to-red ratio particularly advantageous in environments such as XKR, where eutrophication is driven by recurrent phytoplankton blooms but water optical properties are periodically altered by runoff-derived suspended matter from the surrounding catchment.

When compared with previous studies, the performance of our B5/B4 model ($R^2=0.81$; $RMSE=2.2$, corresponding to ~2.5% of average in-situ TSI) is consistent with, or in some cases superior to, results reported for other inland waters. For example, Watanabe et al. (2015) achieved $R^2=0.75$ for TSI(Chla) in the Barra Bonita Reservoir using the NIR-to-red ratio, while Vinh et al. (2022) reported $R^2=0.65$ for TSI estimation in urban lakes in Hanoi with a NIR-to-green ratio. In China, Hu et al. (2021) applied the Algal Bloom Index (ABI) from L8 visible bands to 146 lakes and achieved $R^2=0.57-0.62$

depending on turbidity conditions, and Zhou et al. (2019) used a radial basis function neural network with L8 band ratios to estimate TLI, obtaining $R^2=0.73$. Against this backdrop, our results demonstrate that L8-based empirical models can achieve comparably high or even superior accuracy in a small, polluted reservoir where trophic status is strongly dominated by algal dynamics, underscoring the robustness of the NIR-to-red ratio for eutrophication monitoring. These findings suggest that the B5/B4 ratio is particularly suitable for calculating TSI at the scale of individual, highly productive lakes or reservoirs. Nevertheless, its broader applicability across regional lake networks may be limited, since water bodies influenced by high concentrations of inorganic suspended matter or colored dissolved organic matter often exhibit weaker correlations with this index. Differences between these studies and the present work may be partly attributed to variations in water body optical properties and trophic conditions, as several previous studies focused on hypereutrophic lakes or active algal bloom events, whereas XKR is characterized by a high eutrophic state. In addition, discrepancies may also arise from differences in methodological approaches, as empirical band-ratio models, such as those applied here, can respond differently to optical variability compared with machine-learning-based methods.

The spatial distribution of TSI derived from 19 images revealed persistent hotspots in the northern and northeastern zones of the reservoir. These areas

correspond closely with inflow channels draining agricultural land and the vicinity of the Xuan Son Waste Treatment Complex (Figure 10). The alignment of high TSI zones with these land uses suggests that both diffuse nutrient runoff and point-source discharges are major external drivers of eutrophication in XKR. Peaks observed in summer months further emphasize the interaction between catchment pressures and seasonal hydrological and thermal regimes.

Despite the promising results, several limitations of this study should be acknowledged. First, the TSI retrieval model was based on an empirical approach, calibrated with a limited number of in-situ measurements. While the B5/B4 ratio showed strong correlations with trophic status, empirical models are site-specific and may have limited transferability to other reservoirs with different optical properties or land-use settings. Second, data availability constrained temporal resolution: only four field campaigns were conducted for calibration and validation, and the use of Landsat imagery was restricted by its 16-day revisit cycle and frequent cloud cover, which can obscure key bloom events. Finally, the model did not explicitly separate the effects of phytoplankton and suspended sediments, which may vary seasonally and spatially in a small, runoff-impacted reservoir like XKR. These limitations suggest that future work should integrate multi-sensor observations, higher-frequency monitoring, and semi-analytical or machine-learning approaches to improve robustness and generalizability.

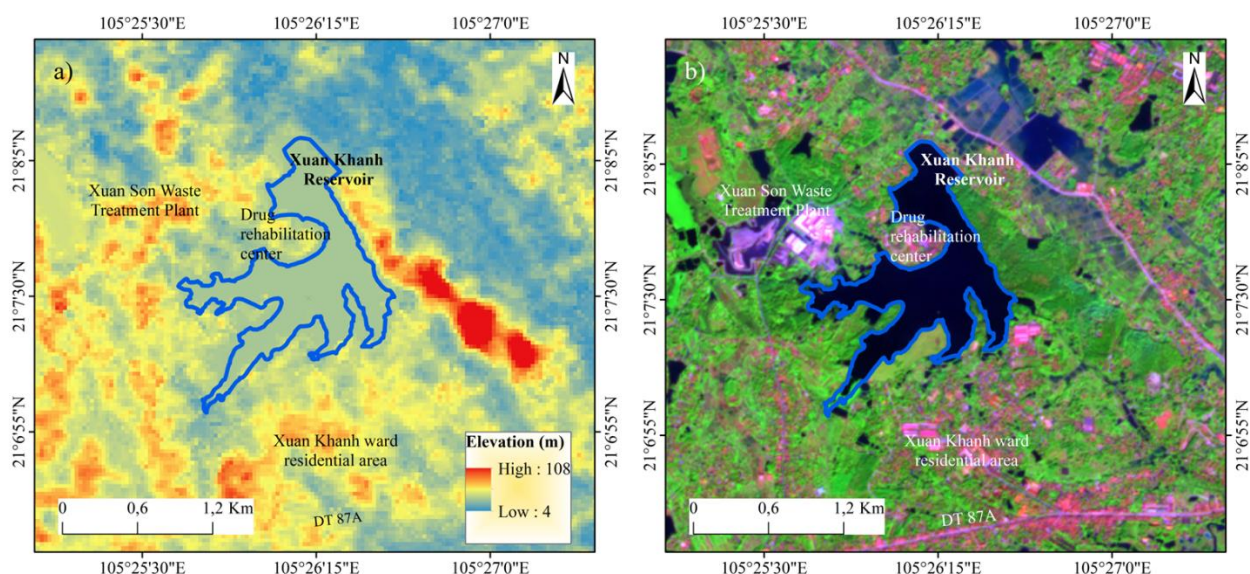


Figure 10. Catchment of XKR showing (a) elevation patterns and (b) major surrounding land uses. Key features include the Xuan Son Waste Treatment Plant, a drug rehabilitation center, and adjacent agricultural and residential areas, all of which represent potential nutrient sources influencing water quality in the reservoir.

Looking ahead, future research should aim to overcome these limitations by combining multi-sensor datasets (e.g., Landsat 8/9, Sentinel-2 MSI, Sentinel-3 OLCI) to improve temporal resolution and reduce cloud-related data gaps. The integration of UAV- or drone-based hyperspectral imagery with satellite observations could also provide higher spatial and spectral detail, helping to disentangle the respective influences of phytoplankton and suspended sediments on reflectance. Moreover, the application of machine learning and semi-analytical approaches has the potential to enhance model robustness, enabling more transferable algorithms for eutrophication monitoring across diverse reservoir systems. Such advancements would provide local managers with more reliable, near-real-time information to support the sustainable management of small, nutrient-enriched reservoirs like XKR.

Although eutrophication indicators can be effectively estimated from satellite imagery, the processes and sources driving eutrophication are strongly influenced by factors such as water-level regulation, microbial dynamics, and reservoir management practices (Li et al., 2019; Oyege et al., 2024; Wen et al., 2025). Future studies would benefit from integrating remote sensing with hydrological and ecological analyses to better resolve these processes.

5. CONCLUSION

This study shows that XKR, a small and heavily impacted freshwater system, has persisted in a highly eutrophic to hypereutrophic state over the past four years, with clear seasonal fluctuations driven by wet-season runoff, wastewater discharges, and land-use pressures in its catchment. By integrating in-situ measurements (66 samples from four campaigns) with Landsat 8-LaSRC reflectance data, we developed a robust band-ratio model ($B5/B4$) that accurately estimated TSI ($R^2=0.80$, $RMSE=0.04$) and successfully captured both spatial heterogeneity and temporal dynamics of eutrophication. While focused on XKR, the reservoir also serves as a representative case of many small, polluted water bodies in rapidly urbanizing and agricultural landscapes. The results highlight not only persistent nutrient enrichment and localized hotspots of trophic stress but also the broader need for integrated management measures-nutrient load reduction, wastewater treatment, land-use regulation, and catchment-scale restoration-to protect freshwater quality. More broadly, this research demonstrates the value of freely available medium-

resolution satellite imagery (Landsat 8/9) as a cost-effective, transferable, and policy-relevant tool for monitoring eutrophication in small tropical reservoirs.

With proper site-specific recalibration, the approach can be scaled to other data-limited regions, supporting both scientific understanding and practical water resource and environmental management worldwide. In practice, the proposed Landsat-based framework could support routine eutrophication monitoring at seasonal to annual scales, providing timely information to guide nutrient management, wastewater control, and early warning of trophic deterioration in small reservoirs.

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AUTHOR CONTRIBUTIONS

Experimental Run and Data Collection: Ngoc TA, Loi DT, Chien NQ; Methodology and Validation: Thao NTP, Manh NV, Ha NTT; Writing-Original Draft Preparation: Thao NTP, Manh NV, Ha NTT; Formal Analysis, Data Curation, and Visualization: Ngoc TA, Loi DT, Chien NQ; Writing-Review and Editing: Thao NTP, Manh NV, Ha NTT; Supervision: Ha NTT.

DECLARATION OF CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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The Phytoremediation Potential of *Lemna minor* L. on Heavy Metal Accumulation, Biochemical Responses, and Growth Tolerance

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ABSTRACT

Duckweed (*Lemna minor* L.) is an efficient aquatic plant that accumulates heavy metals. This study aimed to investigate the ability of duckweed. To accumulate selected heavy metals (Ni, Cu, Zn, Fe, Ba, Mn, and Co) at 5 mg/L concentrations of each metal, and to study the effects of metals on plant growth and biochemical changes in the plant. This study was conducted for 14 days to control the environmental conditions. The accumulation of metal inside the plant tissue, bioconcentration factor (BCF), and relative growth rate (RGR) were measured at the end of the experiments, while plant fresh and dry weight, total chlorophyll, and protein and proline contents were measured at the beginning and end of the experiments. The results showed that the highest metal accumulation in plant tissue and BCF were 4.112 and 0.822, respectively, in the iron treatment, while the lowest values were 2.334 and 0.466, respectively, in the Ba treatment. The highest reduction in fresh weight and growth percentage was in the Ba treatment, the highest reduction in chlorophyll content was in the Ba treatment, and the lowest protein content was in the Cu treatment. Therefore, the results indicate that Duckweed can tolerate selected heavy metals and can be used in phytoremediation technology.

HIGHLIGHTS

- *Lemna minor* demonstrates strong potential for phytoremediation of metal-contaminated water
- Duckweed efficiently removed iron while maintaining high growth performance
- Physiological stress indicators guide metal-specific remediation strategies

1. INTRODUCTION

Recently, rapid industrialization, population growth, and careless use of natural resources have produced wastewater with various organic and inorganic pollutants that find their way to natural surface water, which can reduce the quality of the natural water discharged into it (Al-Nabhan and Al-Abbawy, 2021; Fei et al., 2022; Garai et al., 2021).

Although some of these metals have beneficial effects as micro- and macronutrients, approximately 20 kinds of these metals have no beneficial effect on all organisms, and they are toxic at any concentration for both humans and the environment (Vardhan et al., 2019). The dangerous effects of heavy metals are not biologically degradable and accumulate in food, water, plants, and sediments before making their way up the food chain to humans (Fei et al., 2022;

Goncharuk and Zagorskina, 2023). Before entering the receiving environment, large amounts of these components must be removed (Tatar et al., 2019).

Traditional heavy metal treatments include chemical precipitation, electrochemical processes, coagulants, flocculation, and ion exchange (Ubuza et al., 2020). A biological technology called Phytoremediation uses plants to remove pollutants and heavy metals from wastewater. It is an inexpensive and environmentally responsible way to dispose of trash while simultaneously saving money, protecting the environment, and improving aesthetics (Awa and Hadibarata, 2020; Jagetiya and Kumar, 2020).

Among aquatic plants, *L. minor* L., commonly known as duckweed, can remove pollutants from wastewater because of its high passive uptake through the root cell wall micropores (Ubuza et al., 2020).

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Deposited heavy metals increase efficiency, and pollutants are transported to plants via water. The potential of duckweed is constrained in biotic and immobile environments such as wetlands.

Despite such limitations, duckweeds are efficient phytoremediators and purifiers of contaminated water bodies because of their rapid reproduction and sensitivity to pollution (Zhou et al., 2023). Their accumulation enables the absorption of metals and metalloids into the cellular biomass. The monocotyledonous aquatic plant *L. minor* grows in both tropical and temperate climates. In marshes, slow-moving and nutrient-rich water grow well and form a mat on its surface. It grows more slowly at temperatures below 10°C and above 40°C than at the ideal growth temperature of 20-30°C (Al-Nabhan, 2022).

Several studies have confirmed duckweeds capacity for heavy metals accumulation. Thayaparan et al. (2015) studied the phytoremediation capacity of *L. minor* for chromium absorption in soil and water. The plant demonstrated a notable ability to absorb Cr at varying doses. Growth increased until the third day; however, the bioconcentration factor declined as the chromium in the solution grew. According to these findings, *L. minor* is an exceptional accumulator of chromium and may be used to remove chromium from streams, as traditional remediation techniques are insufficient.

Similarly, Neidoni et al. (2018) studied the ability of plants to accumulate and tolerate zinc, copper, and nickel; the quality of wastewater both before and after treatment; and the capability of plants to accumulate heavy metals from wastewater. According to Azeez (2021), *Utricularia vulgaris* and *Lemna minor* can significantly remove manganese (Mn), copper (Cu), and zinc (Zn) from wastewater with removal efficiencies over 68%. Thus, these plants demonstrate great potential for eco-friendly wastewater treatment and can be used as bioindicators of water quality.

Further studies have demonstrated the ability of some plant species to reduce pollutants from soil-contaminated variations. For example, *Polypogon monspeliensis* can reduce total petroleum hydrocarbon levels by up to 64.85% in soils contaminated with 20 g/kg over 30 d. The high translocation factor (TF>1) indicates good growth at lower contamination levels (Azeez et al., 2023).

Additionally, the bioaccumulation of heavy metals (Fe, Ni, Cr, Zn) in six species of aquatic plants from Al-Hawizeh Marsh was investigated by Al-

Abbawy et al. (2021). According to this study, submerged plants, such as *Ceratophyllum demersum* and *Najas marina*, had the highest bioaccumulation capacities, particularly for Cr, which are above the limits allowed by the WHO. This suggests their potential role in the bioindication and remediation of water bodies polluted by heavy metals.

Research on *Lemna minor* phytoremediation of heavy metals has grown substantially, driven by increasing aquatic contamination from industrial, agricultural, and urban sources, and reinforced by its rapid growth, low cost, and demonstrated ability to accumulate metals such as cadmium, lead, chromium, copper, and iron (Ali et al., 2020; Islam et al., 2024). Recent studies have shown that uptake can be enhanced and that removal efficiency is coupled with complex physiological responses, including oxidative stress markers such as proline and chlorophyll degradation (Aslanzadeh et al., 2024; Mobin et al., 2025). Despite these advances, inconsistent findings regarding *L. minor*'s accumulation capacity and tolerance affected by factors such as pH, metal speciation, and exposure regime reflect heterogeneous methodologies and incomplete integration of uptake with stress signaling (Shaari et al., 2022).

The present study attempted to fill this gap by exploring the joint accumulation of multiple Heavy Metals (Zn and Cu) in *L. minor*, as well as essential biochemical responses (antioxidant enzyme activities) and growth behavior under different contamination circumstances. Incidentally, the inclusion of growth parameters, metal-uptake efficiency, and physiological markers allows a better appreciation of this feature to compete amongst plants.

To our knowledge, this is one of the few studies that conducted research on the relations between accumulation as bioaccumulation indicators and biochemical responses in *L. minor* under the complex contamination environment of wastewater sludge leachate enriched with heavy metals in a long-term response.

These findings are anticipated to give a substantial contribution to the use of *L. minor* as a phytoremediator and even develop an actual solution for eco-friendly wastewater treatment systems in developing countries.

2. METHODOLOGY

2.1 Aquatic plant collection and acclimation

Lemna minor L. plants were collected from the Al-Hammar marsh in Basrah Province, south of Iraq.

The plants were transported to the laboratory in labeled plastic bags.

After washing several times with tap water to remove dust and dirt, it was placed in a 20-liter basin with tap water that was free of chlorine with the aerator provided and left to acclimatize to laboratory conditions for a week.

2.2 Heavy metals concentration preparation

Each metal was prepared at a concentration of 5 mg/L using 1,000 mg/L of a metal standard salt that had already been prepared. $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$; $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; ZnSO_4 ; BaCl_2 ; NiCl_2 ; CoSO_4 ; MnSO_4 salt were used to prepare 1,000 mg/L of each metals according to equation bellow and the diluted to prepare desire concentration 5 mg/L of each metal)

$$\text{Weight (g)} = \frac{\frac{\text{mg}}{\text{L}}}{1,000} \times \frac{\text{molecular weight of salts}}{\text{atomic weight of metal} \times \text{no. of atoms}} \times \frac{\text{volume (mL)}}{1,000}$$

and

$$C_1 V_1 = C_2 V_2$$

Where; C_1 : the concentration (1,000 mg/L prepared by salt); V_1 : the volume (mL) needed to prepare 5 mg/L; C_2 : desire concentration (5 mg/L) of each metal; V_2 : volume of metal in each treatment (1 liter).

2.3 Experimental setup

Three duplicates of each metal were placed in 1.6-liter plastic aquariums, which were then filled with one liter of the previously prepared solution at a concentration of 5 mg/L. Hoagland nutrient solution (1%) was used. Three aquariums containing metal-free water were used as controls. About four grams of healthy plants were placed in each aquarium after washing with tap water and distilled water. The experiments were conducted for 14 days.

2.4 Parameters measurement

2.4.1 Plant fresh weight, dry weight and growth percentage

After washing the plant with tap water and distilled water to remove debris and get rid of excess water using filter papers, the fresh weight of the plant was measured using a scale and recorded in grams. The weight was measured in grams, as well as the dry weight, which was determined by drying the fresh plant at 70°C in an oven until the weight was constant.

Growth percentage was calculated according to the equation described by [Ubuza et al. \(2020\)](#):

$$\text{Growth\%} = \frac{\text{final weight after exposure duration} - \text{Initial weight at 0 time}}{\text{Initial weight at 0 time}} \times 100$$

2.4.2 Heavy metal concentration in plant tissue and bioconcentration factor (BCF)

The [ROPME \(1982\)](#) method was used to evaluate the concentration of heavy metals in plant tissue using a Flame atomic absorption spectrophotometer (Buck 210BGP, Germany), and the value was recorded in mg/kg. BCF was calculated according to the equation described by [Neidoni et al. \(2018\)](#).

$$\text{BCF} = \frac{\text{metal concentrations in plant tissue (mg/kg)}}{\text{intital metal concentration in water (mg/L)}}$$

2.4.3 Total chlorophyll content

Total chlorophyll content was determined by the method described by [Arnon \(1949\)](#). Using 20 mL of 80% acetone, about 0.2 grams of fresh weight was extracted. A centrifuge (3,000 rpm) set at 5,000 rpm for ten minutes was used to separate the clear solution. Total chlorophyll content was measured at optical densities of 645 and 663 nm using a spectrophotometric technique (T80 UV/VIS, Instrument Ltd PG, UK). The concentrations are given in units of µg/g.

$$\text{Total chlorophyll (µg/g)} = (12.7 \times \text{OD } 663) + (16.8 \times \text{OD } 645)$$

Where; OD: optical density at 645 and 663 nm.

2.4.4 Protein content

The methods described by [Bremner and Mulvaney \(1982\)](#), [Okwu et al. \(2006\)](#), and [AOAC \(2000\)](#) were used to determine protein content. Multiplying the total nitrogen by 6.25 gives its representation.

2.4.5 Proline content

The proline content was determined using the procedure outlined by [Troll and Lindsley \(1955\)](#). Five milliliters of 95% ethanol were combined with 0.2 grams of dry, powdered plant for an hour, and then the mixture was centrifuged for five minutes at 5,000 revolutions per minute. Near drying, the translucent portion of the extract had disappeared. The mixture was supplemented with 2 mL of distilled water. Using spectroscopy at 520 nm, the proline content of 1 mL

extract solution was determined in units using the proline standard curve.

2.4.6 Tolerance index rate percentage (TIR)

The tolerance index rate was calculated according to the equation mentioned in Wilkins (1978).

$$\text{TIR}\% = \frac{\text{dry weight of plant in metals treatment}}{\text{dry weight in control treatment}} \times 100$$

2.5 Statistical analysis

Data were analyzed using Statistical Package for Social Science (SPSS) version 23. Statistical analyses were conducted using one-way analysis of variance (ANOVA) to determine differences in plant fresh weight among treatments. Post hoc comparisons were performed using Tukey's honestly significant difference (HSD) test at a significance level of $p < 0.05$.

3. RESULTS

3.1 Accumulation of heavy metals by plant tissues and bioconcentration factor (BCF)

At the end of the experiment, *L. minor* tissues exhibited varying capacities to accumulate the tested heavy metals (Figures 1 and 2), with statistically significant differences among treatments ($p < 0.05$). Of the metals tested, the greatest levels of absorption were with Iron (Fe), averaging 4.112 mg/g, whereas the least was observed in Barium (Ba) 2.334 mg/g).

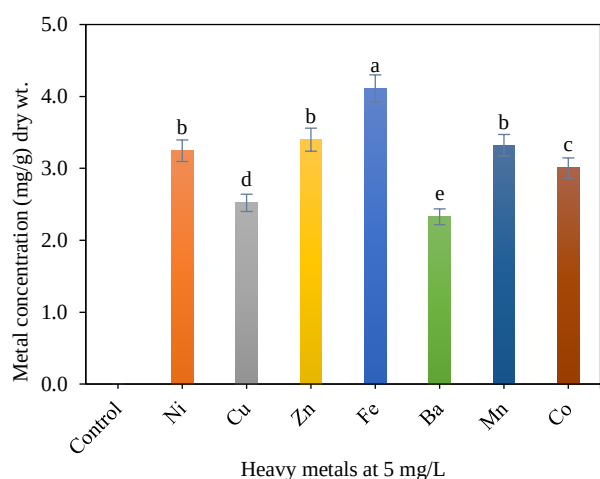


Figure 1. Metal concentration (mg/g dry weight) in plant tissues exposed to 5 mg/L of different heavy metals. Values represent mean $\pm$ standard error (SE), $n=5$.

Correspondingly, the bioconcentration factor (BCF) values also differed widely among the treatments. The highest BCF was obtained from iron (Fe) at 0.822, indicating maximum uptake by the plant, whereas Barium (Ba) had a BCF value of 0.466, representing the least.

This demonstrates the capacity of duckweed to accumulate heavy metals in a specific manner, depending on the specific metal type and its interaction with the plant tissues.

3.2 Fresh weight and growth percentage

The results (Figures 3 and 4) showed that every metallic treatment lowered the fresh weight of *L. minor*, except for the Fe treatment, which promoted growth. The greatest reduction was observed in the fresh weight of plants treated with Barium (Ba), with an average fresh weight of 2.090 g and the lowest relative growth percentage at 0.505 g. Iron (Fe), in contrast, produced increased weight in plants, with values of fresh weight as high as 4.314 g and a relative growth percentage of 1.071, closely similar to the control values of 4.476 g and 1.104 g, respectively.

A statistically significant difference ($p \leq 0.05$) was observed between the treatments and the control based on ANOVA, confirming the varied effects of metals on plant growth.

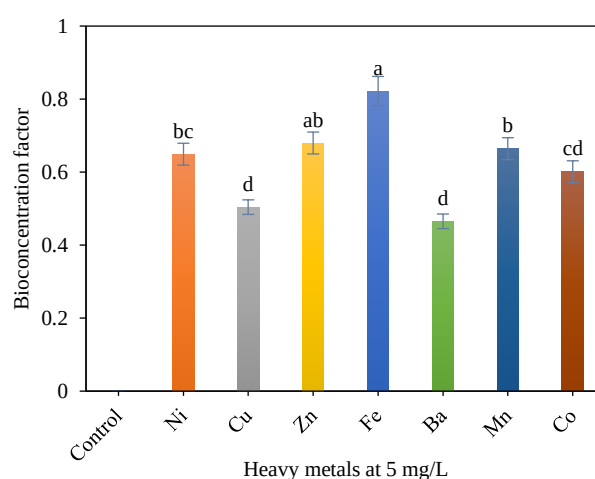


Figure 2. Bioconcentration factor (BCF) of metals in plant tissues exposed to 5 mg/L metal concentration. Values represent mean $\pm$ standard error (SE), $n=5$.

3.3 Total chlorophyll content

As shown in Figure 5, the initial total chlorophyll content of *Lemna minor* was 4.552 $\mu\text{g/g}$. After 14 days of exposure, it was observed that the

treatment influenced the chlorophyll content. For the iron (Fe) treatment, a slight increase was observed, with an average total chlorophyll content of 4.197 $\mu\text{g/g}$. In contrast, the control recorded the highest

value of 4.941 $\mu\text{g/g}$. However, all other metal treatments reduced the total chlorophyll content compared with the control treatment. The most dramatic effect was observed in the Mn treatment (2.174 $\mu\text{g/g}$ at 5 mg/L).

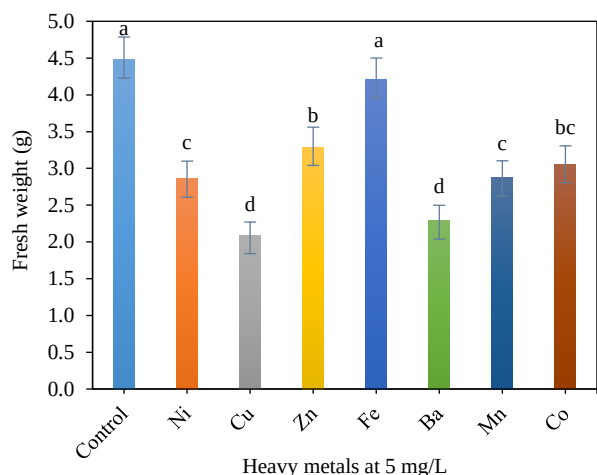


Figure 3. Effect of different heavy metals (5 mg/L) on plant fresh weight. Values represent mean $\pm$ standard error (SE), n=5. Different letters above bars indicate significant differences according to one-way ANOVA followed by Tukey's HSD test ($p<0.05$).

Statistical analysis (ANOVA) revealed significant differences between the treatments and their controls ($p\leq 0.05$). Therefore, heavy metals have different effects on chlorophyll biosynthesis and degradation.

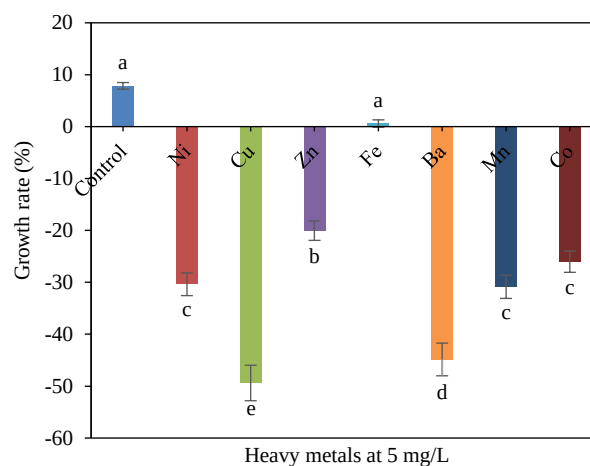


Figure 4. Percentage growth response of plants exposed to different heavy metals at 5 mg/L. Values represent mean $\pm$ standard error (SE), calculated relative to the control (n=5).

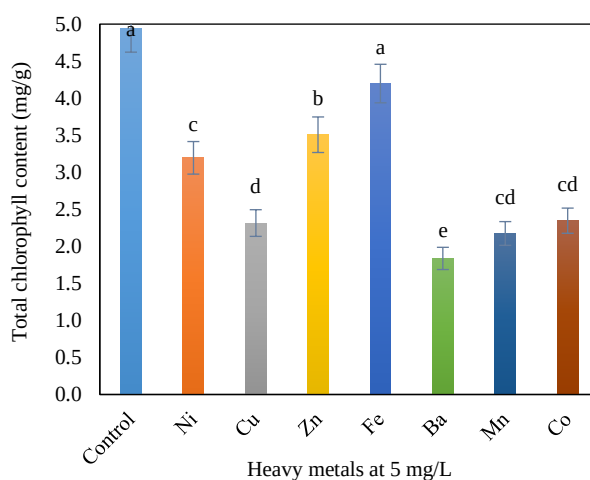


Figure 5. Effect of different heavy metals (5 mg/L) on total chlorophyll content of plants. Values represent mean $\pm$ standard error (SE), n=5. Different letters above bars indicate significant differences according to one-way ANOVA followed by Tukey's HSD test ($p<0.05$).

3.4 Protein content

The initial protein content of *L. minor* was 31.43%. After 14 days of exposure to heavy metals (Figure 6). All treatments showed a decline in the amount of protein with varying severities due to exposure to heavy metals after 14 days. The least reduced content was found in the iron (Fe) treatment, which had a protein content of 27.89%, indicating that Fe had only a minor negative effect on protein synthesis. About the copper (Cu) treatment, the most

reduction occurred, and protein content decreased to 21.613%, indicating how toxic it was regarding copper's cellular activities. These data suggest that the level of protein reduction is directly related to metal toxicity. The differences between treatments and control with a significant p value ($p\leq 0.05$) in ANOVA statistical analysis confirmed significance in treatments and controls, emphasizing differences in the adverse effects of heavy metals on protein metabolism.

3.5 Proline content

Initially, *L. minor* had a proline concentration of 31.33 mg/g. After 14 d of exposure to heavy metals (Figure 7), all treatments increased the levels of proline, illustrating a physiological response to heavy metal-induced stress. The highest observed concentration of proline was found in copper (Cu) treatment, which had an average of 79.403 mg/g, corresponding to another strong evidence of physiological stress due to Cu toxicity. In contrast, the lowest proline concentration was recorded for the

treatment control, with an average value of 34.25 mg/g since significant stressors were not available.

Heavy metals themselves substantially increase the concentration levels of proline, indicating that it may serve as a potential osmoprotectant as well as an antioxidant, thereby preventing oxidative stress from being imparted by exposure to metals. Statistically, ANOVA showed there are significant differences between treatments and control ($p \leq 0.05$), showing how heavy metals influence proline accumulation differently.

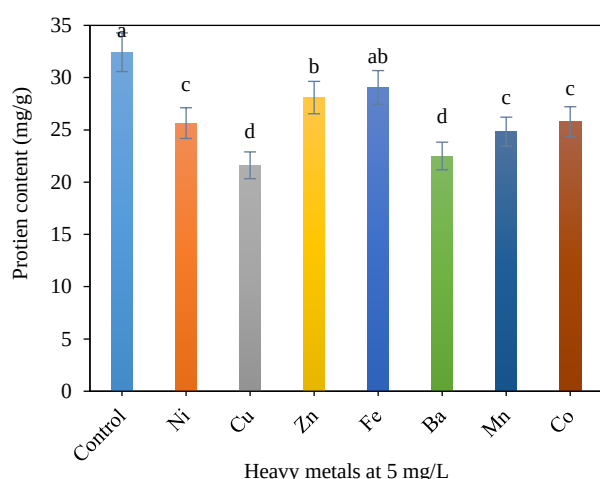


Figure 6. Effect of different heavy metals (5 mg/L) on protein content of plants. Values represent mean $\pm$ standard error (SE), $n=5$. Different letters above bars indicate significant differences according to one-way ANOVA followed by Tukey's HSD test ($p < 0.05$).

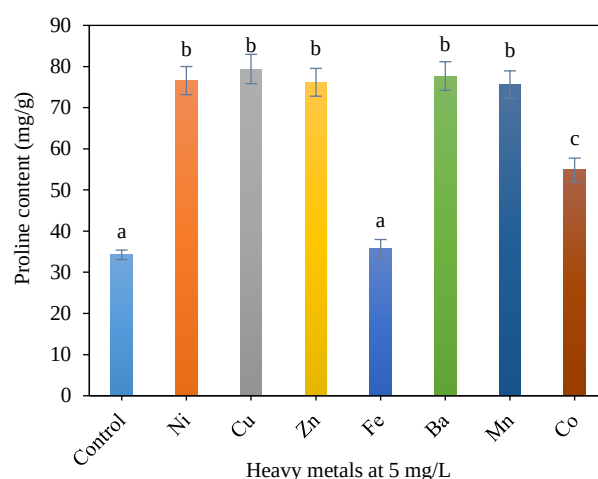


Figure 7. Effect of different heavy metals (5 mg/L) on proline content of plants. Values represent mean $\pm$ standard error (SE), $n=5$. Different letters above bars indicate significant differences according to one-way ANOVA followed by Tukey's HSD test ($p < 0.05$).

3.6 Tolerance index rate (TIR %)

Figure 8 showed that at different heavy metal treatment concentrations of treatment concentration at 5 mg/L, after 14 days of exposure to the heavy metals, the tolerance index rate (TIR) of *L. minor* L. varied widely among metals. The highest value of TIR was obtained in treatment with iron (Fe), which was 97.57%, indicating a high tolerance of the plant against iron. The lowest TIR was recorded for the manganese (Mn) treatment, which indicated that the TIR value was 56.79%, showing a considerable reduction in plant tolerance under manganese exposure.

As featured by these results, the type of heavy metal affects the tolerance of *L. minor* L. Consistent with that, some metals (as Fe) were found to be less detrimental to the growth and physiology of plants than others (as Mn). ANOVA statistical analysis somehow proved the significant difference of treatments, because tolerances varied among metals ($p \leq 0.05$).

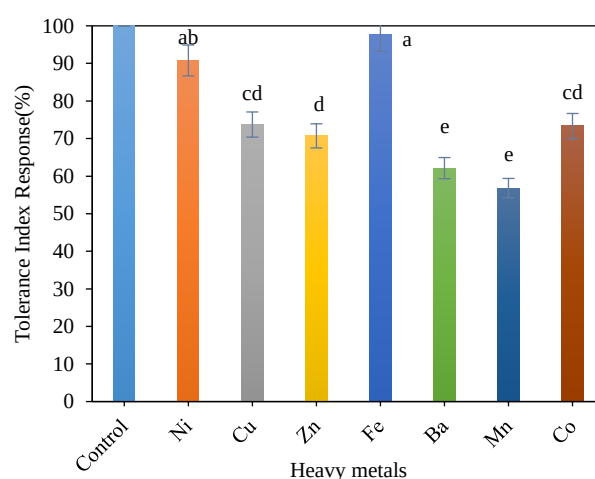


Figure 8. Tolerance index response (TIR %) of plants exposed to different heavy metals at 5 mg/L. Values represent mean $\pm$ standard error (SE), $n=5$. Different letters above bars indicate significant differences according to one-way ANOVA followed by Tukey's HSD test ($p < 0.05$).

4. DISCUSSION

The accumulation of metals inside the plant tissue is the process by which the plant absorbs the metal from the medium, such as water or soil. Metal accumulation in the plant increased with the duration of exposure. Moreover, the Bioconcentration factor (BCF) is an effective tool for assessing the plant's ability to accumulate heavy metals (Aziz et al., 2023). The BCF value depends on the initial metal concentration. Lower metal concentrations exert reduced toxicological effects on plants, thereby enhancing their capacity for metal uptake; however, plant growth responses vary according to metal type, varying between metals at the same concentration. Lower metal concentrations exert reduced toxicological effects on plants, thereby enhancing their capacity to absorb heavy metals from the surrounding environment. This effect may either stimulate or inhibit plant growth, depending on the metal involved. This effect may either enhance or inhibit plant growth, depending on the metal involved, even at identical concentrations. In this study, the accumulation of Iron slightly enhanced plant growth as a micronutrient, and other metals accumulated with different values depending on their toxicity on plants, such as Cu, Ba, and Mn. For instance, Du et al. (2020) reported a BCF of 0.75 for iron in *Brassica juncea*, which aligns with our findings that iron promotes growth. The first sign of plant toxicity is a reduction in plant growth. This may be caused by changes in the structure and function of the cell membrane brought on by ROS, which can disrupt the movement of nutrients and water between the cell and its surroundings, disrupt the balance of nutrients, and inhibit the activity of enzymes, all of which can impair physiological processes. Additionally, the efficiency of photosynthesis is decreased when the chlorophyll content is damaged.

Plant development is reduced when exposed to heavy metals (HM), mostly because the photosynthetic system is harmed (Hu et al., 2023). For example, Du et al. (2020) found that varying concentrations of Zn significantly impacted plant growth, biomass output, and root length. According to recent studies, *Lemna minor* L. plants are under stress since their biomass production is slightly decreased or increased depending on metal, and growth decrease is a general response to heavy metal stress. In the present study, *Lemna minor* exhibited enhanced growth under iron exposure, likely because iron functions as an essential micronutrient. In contrast, exposure to other

metals resulted in growth inhibition to varying degrees. Bortoloti and Baron (2022) also noted significant reductions in biomass in plants exposed to heavy metals, with reductions of up to 40% in some species.

Plant leaves suffer chlorosis because of heavy metal stress, which lowers the amount of photosynthetic pigment in the thylakoid membrane. This is caused by three primary factors inhibiting the anabolism of chlorophyll, lowering the activities of antioxidant enzymes, and competing for active sites with Mg^{2+} in chlorophyll molecules (Sperdoui et al., 2022). Kapoor et al. (2019) reported a reduction in total chlorophyll content under Cd stress, with values dropping from 5.0 $\mu\text{g/g}$ to 3.0 $\mu\text{g/g}$ at 6.0 mmol/L, which is consistent with our findings where chlorophyll content decreased significantly in treatments with metals like manganese. According to An et al. (2019), Cd stress inhibits the synthesis of chlorophyll in cotton leaves, and when the concentration of metal increases, the amounts of total chlorophyll, chlorophyll a, and chlorophyll b drop dramatically. This outcome concurred with Khan et al. (2024) and Al-Nabhan (2022).

The reduction in protein content varied among treatments and is likely attributable to ribosomal interference, which disrupts protein synthesis. Additionally, metal-induced reactive oxygen species (ROS) generation can modify sulfhydryl ($-SH$) groups in proteins, altering their structure and reducing protein synthesis (Khan et al., 2024). Proline is an essential amino acid involved in plant stress responses, particularly under heavy metal toxicity. The concentration of proline frequently rises as a defense mechanism in plants exposed to heavy metals. Under stress, proline is produced from glutamate. When the proline is bound by metal, its free concentration and toxicity are reduced during the recovery from metal stress. This happens because osmoregulation keeps the cellular osmotic balance under severe metal stress. Proline breaks down to produce energy and the carbon skeleton needed for metabolic processes (Khan et al., 2024). These results consist with Al-Nabhan (2023), who reported proline levels increasing from 30 mg/g to 75 mg/g under heavy metal stress. This suggests that proline plays a crucial role in osmoregulation and oxidative stress mitigation.

An indicator of a plant's capacity to thrive in the presence of a specific metal concentration is the tolerance index (Bianconi et al., 2013). In this study, the plant tolerates Ni better than others. The decrease

in tolerance index rate was attributed to a decrease in dry weight in the studies compared to the control. This is in agreement with Umebese and Motajo (2008), who found that TIR values for various metals varied significantly, with nickel showing better tolerance than lead.

5. CONCLUSION

The present results show that *Lemna minor* selectively accumulates and tolerates at least seven heavy metals, indicating its potential for phytoextraction. Interestingly, the roots accumulated iron preferentially compared to plants with a bio-concentration factor and exhibited minimal growth inhibition. This indicates that *L. minor* can assimilate iron while maintaining its vitality.

However, manganese tended to be less tolerant, probably inferring great physiological distress, while copper led to proline, showing osmotic and oxidative stress in plants. These results indicate that *L. minor* can be used for the phytoremediation of iron-laden waters. Nevertheless, in environments with high levels of phytotoxic metals, such as manganese or copper, supplementation or complex treatments may be needed to attenuate potential biomass decrease.

The physiological and biochemical indicators used in this study offer useful insights into the evaluation of plant stress during phytoremediation. Further studies are necessary to confirm these trends under field conditions, and considerations should also be made for the safe disposal and treatment of metal-loaded biomass. Overall, our results highlight the potential use of *L. minor* in environmental remediation applications, with a special emphasis on heavy metal pollution as an important ecological burden.

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AUTHOR CONTRIBUTIONS

Conceptualization, D.A., E.M., and N.M.; Visualization, Z.F.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Land Use and Land Cover Dynamics of Small Inhabited Islands in South Bangka, Bangka Belitung, Indonesia (2004-2024)

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ABSTRACT

Anthropogenic land use and cover changes pose a significant threat to small island ecosystems, yet systematic monitoring remains limited. This study analyzes LULC dynamics over 20 years (2004-2024) on three inhabited islands in South Bangka, Bangka Belitung, Indonesia. The objectives were to assess LULC changes, evaluate their impacts on biodiversity, and examine the effectiveness of existing policies using multi-temporal Landsat and Sentinel-2 imagery. The supervised classification achieved an overall accuracy of 85.3-91.2% with Kappa coefficients of 0.82-0.89, indicating substantial to nearly perfect agreement. The results revealed distinct transformation patterns across the islands. Tinggi Island demonstrated resilience through the recovery of secondary dryland forests (from 68.52 ha to 113.48 ha), despite the presence of illegal tin mining activities that created artificial wetland systems. In contrast, Kelapan Island faced severe degradation, with extensive forest loss and habitat fragmentation. This resulted in a 29.5% decline in mean patch size and a critical loss of connectivity. Conversely, Pongok Island showcased successful conservation efforts, significantly expanding its mangrove ecosystem, which enhanced its blue carbon capacity, even amid agricultural intensification. The assessment of biodiversity impacts confirmed that maintaining patch sizes above 20 hectares and ensuring high connectivity are essential thresholds for species conservation. However, current LULC management policies demonstrate limited effectiveness due to regulatory gaps between marine and terrestrial governance frameworks. The study concludes that integrated conservation strategies, including adaptive management and corridor restoration, are urgently needed to balance development pressures with the preservation of ecosystem integrity.

HIGHLIGHTS

- Multi-temporal Landsat-Sentinel fusion analyzed 20-year LULC dynamics.
- Supervised classification achieved 85-91% accuracy with Kappa 0.82-0.89.
- Three islands showed distinct patterns: recovery, degradation, and conservation.
- Patch size >20 ha and high connectivity are critical for species survival.
- Marine-terrestrial governance gaps limit conservation policy effectiveness.

1. INTRODUCTION

Anthropogenic transformations in land use and land cover (LULC) are significant drivers of global environmental change, adversely affecting ecosystem integrity, biodiversity, and human well-being (Baidoo et al., 2023; Kusiima et al., 2022; Smith et al., 2019). These changes have accelerated in recent decades due to population growth, economic development, and

technological advancements, placing unprecedented pressure on terrestrial ecosystems (Rachman et al., 2024; Zhang et al., 2025a). Since 1960, global land conversion has increased by 50%, with Small Island Developing States (SIDS) experiencing even higher rates due to limited land and intense development pressures (UNEP, 2023).

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Small islands ($\leq 2,000$ km²) are particularly vulnerable, hosting 15-20% of terrestrial species despite occupying only 5.5% of Earth's land (Kueffer and Kinney, 2017; Médail, 2017). Land use changes in small islands occur 2-3 times faster than in continental regions, with over 40% of tropical small islands losing more than 10% of their natural cover each decade (Ahmed et al., 2023; Chen et al., 2023). These changes involve complex interactions between proximate causes and underlying drivers (Sisay et al., 2024).

Recent advancements in remote sensing and Geographic Information Systems (GIS) have significantly improved our capacity to monitor LULC dynamics, particularly in remote areas where ground surveys are challenging (Faruque et al., 2022; Singh et al., 2020). Since 1972, the continuous flow of satellite imagery from sources like Landsat has enabled long-term detection and analysis of changes in land cover (Masek et al., 2020). The 30-meter resolution and consistent temporal coverage of the Landsat archive are invaluable for monitoring small islands, where even minor changes have significant ecological impacts (Hemati et al., 2021; Radeloff et al., 2024).

Comprehensive monitoring is essential in small island environments, where geographic isolation and limited resources amplify the impacts of land use changes (Kelman, 2018; Setiawati et al., 2023). Examples include Saint Martin Island in Bangladesh, where built-up areas increased from 2.97% to 21.42% between 2005 and 2021 (Ahmed et al., 2023), and Belitung Island in Indonesia, which experienced a greater than 25% decrease in forest cover from 1990 to 2020 (Oktavia et al., 2024).

South Bangka, part of the Bangka Belitung Island Province, encompasses numerous small inhabited islands that illustrate the complex dynamics of LULC characteristic of Indonesian archipelagos. These islands are home to traditional fishing and subsistence agriculture communities (Achmad et al., 2022; Pical and Rahman, 2025). Economic diversification and developmental pressures reshape these livelihoods, leading to mixed strategies incorporating seaweed cultivation and small-scale tourism (Reksa et al., 2021; Rimmer et al., 2021).

Despite their significance, small inhabited islands frequently lack systematic, long-term monitoring of LULC dynamics (Révillion et al., 2019). Most research concentrates on larger regions, resulting in significant knowledge gaps regarding LULC changes on individual small islands (Purnama

and Çoban, 2024). This shortfall limits our understanding of landscape evolution and the underlying factors driving these changes (Li et al., 2023). Enhanced monitoring and detailed LULC mapping are crucial for assisting policymakers in balancing economic development with environmental conservation (Duan et al., 2025; Yetein et al., 2025).

This study presents a comprehensive 20-year analysis (2004-2024) of LULC dynamics on small inhabited islands in South Bangka, utilizing multi-temporal Landsat imagery and GIS techniques. The objectives are to (1) assess the changes in LULC on small inhabited islands from 2004 to 2024, (2) evaluate the impacts of these LULC changes on biodiversity, and (3) evaluate the effectiveness of LULC management policies in small islands.

2. METHODOLOGY

2.1 Study area and data acquisition

This study focused on three small inhabited islands located in South Bangka, Bangka Belitung Province, Indonesia: Kelapan Island, Pongok Island, and Tinggi Island (2°30'S-3°00'S, 106°30'E-107°00'E) (Figure 1).

We utilized multi-temporal satellite imagery from three significant periods: Landsat 7 ETM+ (2004), Landsat 7 ETM+ with high-resolution correction (2014), and Sentinel-2 L2A (2024). All images were captured during the dry season with less than 10% cloud cover to ensure optimal quality. This timeline corresponds with key policy milestones: 2004 serves as the baseline prior to the implementation of formal spatial planning policies; 2014 reflects the period after the South Bangka Regency Spatial Plan was enacted, allowing for a midpoint evaluation; and 2024 provides the most recent observations for assessing long-term effectiveness. The 10-year intervals are effective for identifying significant land-use and land-cover changes, as major transformations tend to unfold over time (Gómez et al., 2016). Cross-sensor radiometric calibration was performed to ensure spectral alignment between the Landsat 7 ETM+ and Sentinel-2 sensors.

Although a higher temporal resolution could capture inter-annual variations, persistent tropical cloud cover and the necessity for consistent dry-season imagery constrained data availability. To supplement our analysis, we incorporated historical land cover maps from the Indonesian Ministry of Environment and Forestry (KLHK) along with local government planning documents for additional

context. Administrative boundary maps were sourced from the Geospatial Information Agency (BIG), and GPS technology was employed for ground-truth data

collection during field surveys in 2024 to validate the accuracy of our classifications.

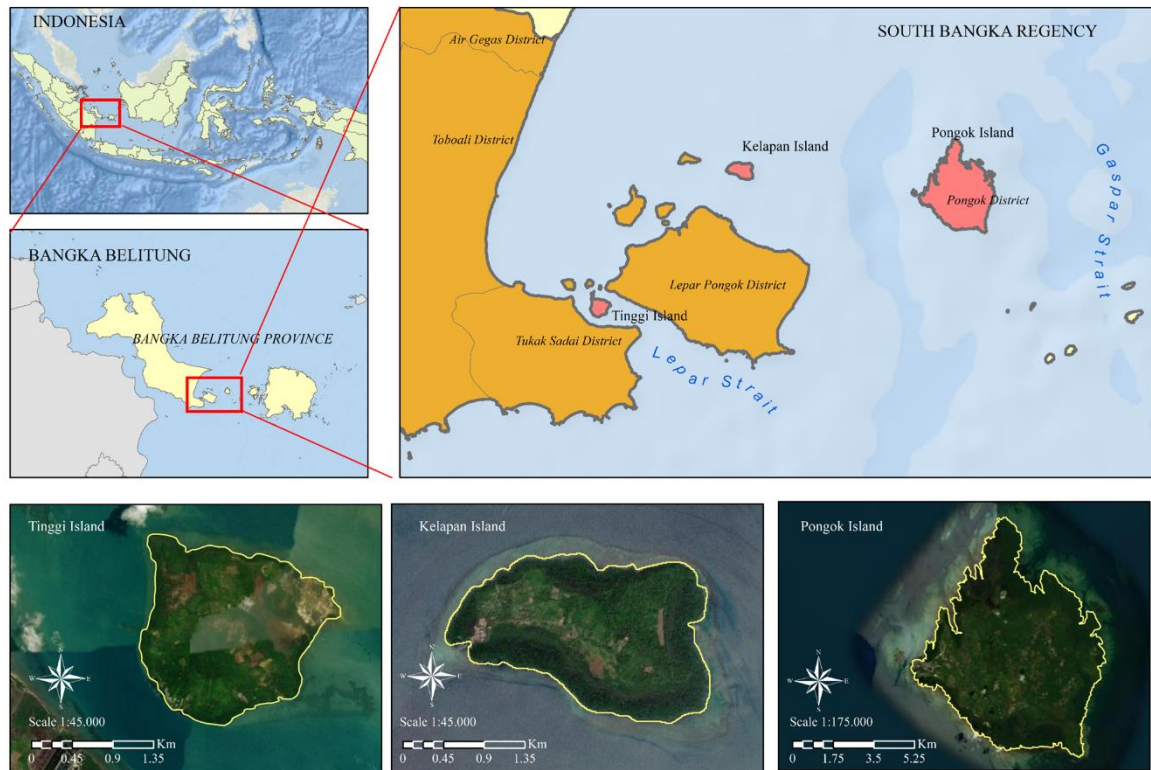


Figure 1. Study the area of LULC on small inhabited islands in South Bangka, Bangka Belitung

2.2 Image processing and classification

Atmospheric correction for Landsat 7 ETM+ imagery was carried out using the Dark Object Subtraction (DOS) method to derive surface reflectance (Shrestha et al., 2019). Sentinel-2 Level 2A data underwent correction using advanced quality-enhancing algorithms. Geometric correction achieved a root mean square error (RMSE) of less than 0.5 pixels, which is essential for accurate quantitative analyses. Furthermore, cross-sensor calibration utilizing pseudo-invariant features helped reduce inter-sensor biases (Khakurel et al., 2021).

Two classification schemes were developed: the Ministry of Environment and Forestry (KLHK) method, which consists of nine categories, and the Intergovernmental Panel on Climate Change (IPCC) framework, comprising six categories. In the IPCC-KLHK crosswalk, 'Wet Shrubland' was classified as 'Grassland' due to similarities in vegetation height, canopy cover, and aboveground carbon stocks (Kauffman et al., 2020). Supervised classification was performed using the Maximum Likelihood Classifier (MLC) within QGIS 3.28, with training samples

collected through stratified random sampling, ensuring a minimum of 50 pixels per class (Congalton and Green, 2019). The spectral separability of class pairs was validated using the Jeffries-Matusita distance, with all pairs exceeding the 1.9 threshold (Legleiter et al., 2016).

Mangrove vegetation was hierarchically classified into primary and secondary types based on canopy density. Primary mangroves, characterized by continuous forest cover from 2004 to 2024, exhibited NDVI values ≥ 0.43 and high texture heterogeneity (GLCM entropy > 4.0). Conversely, secondary mangroves exhibited signs of historical disturbances, characterized by lower NDVI values (0.33-0.42) and a more uniform canopy texture (Pham et al., 2019). Canopy density classifications included dense (NDVI ≥ 0.43), moderate ($0.33 \leq \text{NDVI} < 0.43$), and sparse (NDVI < 0.33) (Faizal et al., 2025). Accuracy was validated using 180 reference points from field surveys conducted in 2024, complementing high-resolution imagery. This was followed by majority filtering and manual editing to minimize noise and correct errors (Phiri and Morgenroth, 2017).

2.3 Accuracy assessment and change detection

The classification accuracy was assessed using 300 stratified random reference points for each island and each time period. This was validated against 2024 field GPS data (n=150 points) and visual interpretation of high-resolution satellite imagery from Google Earth Pro for historical periods. Reference points were allocated proportionally based on class area, following standard remote sensing protocols. The accuracy metrics included overall accuracy (OA), producer's accuracy (PA), user's accuracy (UA), and the Kappa coefficient. The results indicated an overall accuracy ranging from 85.3% to 91.2% across different islands and time periods, with Kappa values between 0.82 and 0.89, signifying substantial to nearly perfect agreement. Most categories showed per-class accuracies exceeding 80%, with mangrove and settlement classes achieving the highest accuracies of over 90%. In contrast, mixed agriculture displayed lower accuracy (75-82%) due to its spectral similarity with shrubland. The accuracy assessment adhered to the protocols outlined, resulting in a minimum overall accuracy of 85%, complemented by Kappa coefficient calculations. Geometric correction achieved RMSE values of 0.42 pixels (Landsat 2004), 0.38 pixels (Landsat 2014), and 0.35 pixels (Sentinel-2 2024), all of which are below the 0.5-pixel threshold required for accurate quantitative analyses. According to [Landis and Koch \(1977\)](#), interpretation guidelines, the Kappa values of 0.82-0.89 indicate 'substantial to almost perfect agreement', confirming the statistical reliability and significance of the classification results ([Desjardins et al., 2023](#)).

Using the post-classification comparison technique in QGIS, a quantitative analysis of the geographical and temporal dynamics of LULC was conducted, producing change matrices for 2004-2024. A comprehensive analysis of forest-to-other land use conversion rates was performed to examine patterns of forest degradation. Forest degradation rates were calculated using the compound interest formula ([Puyravaud, 2003](#)): $r = (1/t) \times \ln(A_2/A_1) \times 100$, where r is the annual change rate (%), A_1 and A_2 are initial and final forest areas (ha), and t is the time interval (years). Landscape metrics were computed using FRAGSTATS 4.2 ([McGarigal et al., 2012](#)): number of patches (NP), mean patch size (MPS=A/NP), edge density (ED=E/A $\times$ 10,000), Shannon diversity index (SHDI= $-\sum(p_i \times \ln p_i)$), and most extensive patch index

(LPI= $\max(a_i)/A \times 100$). Forest connectivity was assessed based on combined MPS and ED values.

2.4 Data analysis

Land use and land cover (LULC) changes from 2004 to 2024 were analysed using descriptive statistics, including area, percentage change, and annual rates. Landscape fragmentation metrics were compared to ecological thresholds for biodiversity conservation. Given the limited data collection (three time points), the focus was on the significance of the observed changes. Data processing was conducted in QGIS and Excel. Limitations included cloud cover, mixed pixel effects, and seasonal fluctuations in vegetation.

3. RESULTS AND DISCUSSION

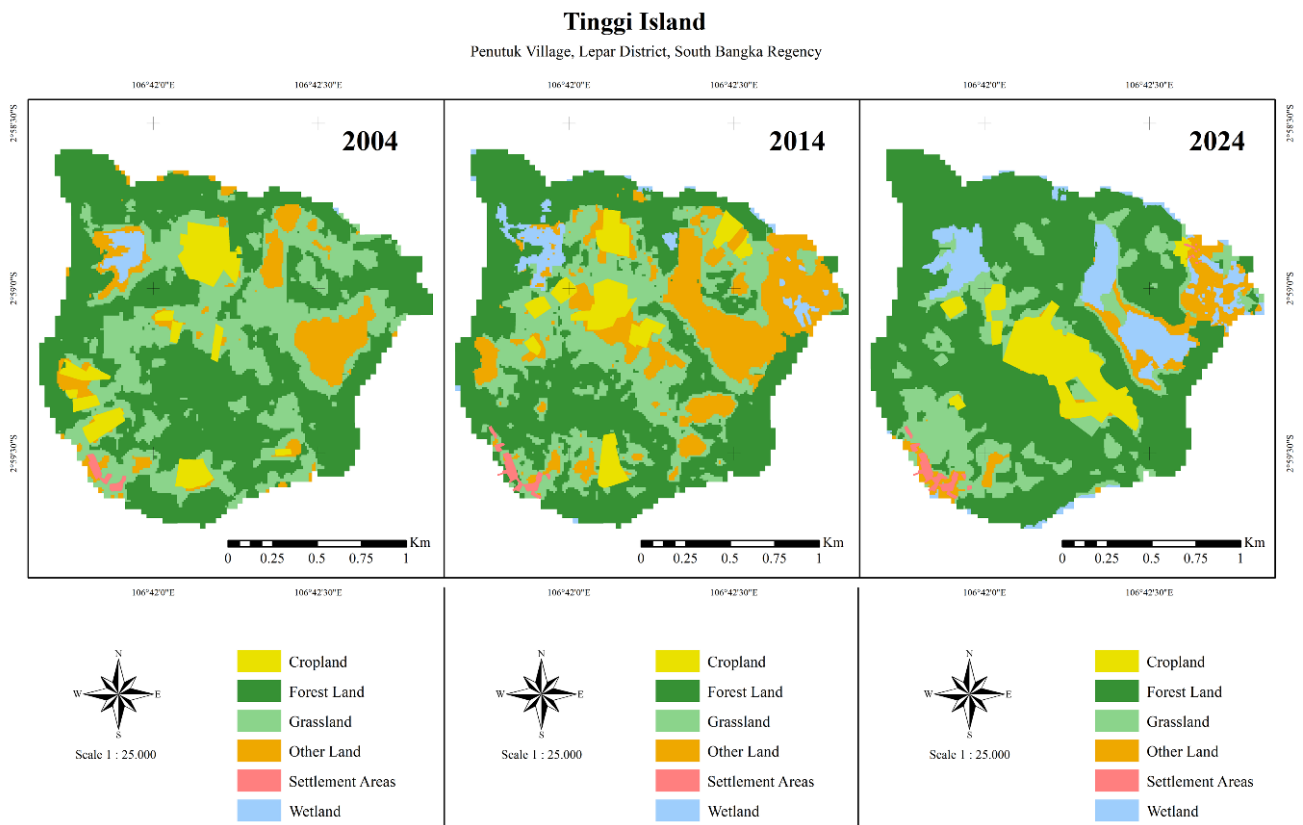
3.1 LULC change patterns and forest resilience

Over the past two decades, changes in land use and land cover (LULC) on the small islands of Bangka Belitung Province have showcased diverse ecosystem dynamics, illustrating the interplay between natural regeneration and human influences. These patterns provide valuable insights into the adaptive capacity of tropical coastal ecosystems, highlighting the impact of local management practices, the distinct characteristics of ecosystems, and the delicate balance between disturbance intensity and regeneration processes.

Tinggi Island exemplifies recovery in secondary dryland forest ecosystems, showcasing 15.05 hectares of regeneration after a decline from 2004 to 2014 (see [Table 1](#) and [Figure 2](#)). This reflects ecological succession theory, which suggests that reduced disturbances aid vegetation restoration. Studies indicate that natural regeneration often results in greater biodiversity than active restoration ([Crouzeilles et al., 2017](#)). Effective forest management strategies on the island, such as preserving residual forest patches, can enhance recovery by providing seed sources ([Zhang et al., 2025b](#)). Moderate fragmentation levels may also support this process, encouraging colonisation by locally adapted species and fostering a diverse ecosystem ([Crouzeilles et al., 2017](#)). Additionally, research by [Mukul et al. \(2020\)](#) notes that initial rapid recovery can lead to changes in tree density as the forest matures, highlighting dynamic growth patterns in Tinggi Island's secondary forests.

Table 1. Changes to the LULC classification of Tinggi Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	19.32	6.12	19.84	6.27	26.60	8.41	+7.28	+2.29
Forest land	Primary mangrove forest	59.80	18.93	61.27	19.37	67.49	21.33	+7.69	+2.40
	Secondary dryland forest	98.43	31.16	68.52	21.66	113.48	35.86	+15.05	+4.70
	Secondary mangrove forest	11.61	3.68	12.12	3.83	7.13	2.25	-4.48	-1.42
Grassland	Wet shrubland	93.37	29.56	79.04	24.99	52.34	16.54	-41.03	-13.02
Other land	Bare ground	28.23	8.94	63.52	20.08	18.55	5.86	-9.68	-3.07
Settlement areas	Settlement areas	1.26	0.40	2.14	0.68	2.54	0.80	+1.28	+0.40
Wetland	Swamp	3.75	1.19	7.66	2.42	25.20	7.96	+21.45	+6.78
	Water bodies	0.07	0.02	2.18	0.69	3.10	0.98	+3.03	+0.96
Total area (ha)		315.84		316.28		316.43			

**Figure 2.** LULC changes in Tinggi Island for the years 2004, 2014, and 2024

The 2.40% increase in primary mangrove forests, alongside the preservation of dryland forests, indicates that conservation efforts are yielding positive results (Table 1 and Figure 2). Mangroves play a vital role as ecosystem engineers, demonstrating significant responsiveness to protective measures. This reinforces the idea that well-implemented conservation strategies can deliver considerable benefits for biodiversity and ecosystem functionality in tropical coastal regions. The increase in wetland areas from 3.75 to 25.20

hectares signifies the conversion of bare ground into wetland, primarily driven by illegal artisanal tin mining activities, locally referred to as ‘tambang inkonvensional’ or TI. These mining operations create excavated pits that eventually fill with water, resulting in artificial wetland systems known as ‘kolong’. The hydrological disruption caused by mining alters natural drainage patterns, leading to water accumulation in former bare mining sites. Over time, these water-filled pits acquire characteristics of

wetland vegetation through the process of natural succession. This transformation raises significant concerns regarding the integrity of the habitat. Research indicates that while secondary forests can regenerate, ongoing human pressures may substantially modify ecosystem composition and structure (Li et al., 2024).

Furthermore, understanding biodiversity recovery in secondary forests requires an examination of the complex interactions among multi-trophic species, especially in fragmented landscapes (Timmers et al., 2025). The interplay between forest recovery and human disturbance on Tinggi Island

demonstrates that while natural regeneration can occur, sustained external pressures may hinder this process, necessitating integrated management approaches (Li et al., 2024). Kelapan Island has recently experienced significant ecological disturbances, resulting in a net loss of 46.06 hectares of secondary dryland forest, which represents 12.02% of its area as established in the 2004 baseline (Table 2 and Figure 3). This degradation level suggests that forest clearing rates have exceeded natural regeneration capacity, potentially approaching ecological tipping points beyond which recovery may be compromised (Obura et al., 2023).

Table 2. Changes to the LULC classification of Kelapan Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	10.07	2.62	7.47	1.94	8.40	2.18	-1.67	-0.44
Forest land	Primary mangrove forest	67.98	17.69	71.58	18.62	74.27	19.30	+6.28	+1.62
	Secondary dryland forest	184.82	48.08	100.89	26.25	138.77	36.07	-46.06	-12.02
	Secondary mangrove forest	21.33	5.55	26.51	6.90	22.99	5.97	+1.66	+0.43
Grassland	Wet shrubland	71.28	18.54	137.97	35.89	118.70	30.85	+47.43	+12.31
Other land	Bare ground	23.30	6.06	36.30	9.44	12.94	3.36	-10.36	-2.70
Settlement areas	Settlement areas	1.52	0.39	1.89	0.49	2.29	0.60	+0.78	+0.20
Wetland	Swamp	4.08	1.06	1.28	0.33	0.68	0.18	-3.40	-0.88
	Water bodies	0.00	0.00	0.47	0.12	5.71	1.48	+5.71	+1.48
Total area (ha)		384.38		384.36		384.74			

Land clearing for agriculture, particularly for clove plantations and selective logging, has led to habitat fragmentation, isolating remaining environmental patches and reducing ecosystem resilience (Hazwan et al., 2022). While primary mangrove forests have expanded by 6.28 hectares (Table 2 and Figure 3), this increase is insufficient to compensate for dryland forest degradation. Research confirms that such ecological disruptions negatively impact biodiversity and ecosystem functioning, highlighting the connection between habitat loss and environmental integrity (Gunawan et al., 2024a).

The 47.43-hectare (12.31%) increase in wet shrubland on Kelapan Island reflects a transitional phase in its ecological trajectory (Table 2 and Figure 3), consistent with the principles of ecological succession theory. Following forest clearing, pioneer species colonize disturbed areas, leading to simplified vegetation structure. This transition may reduce the island's ecological resilience and warrants

conservation attention (Tripathi et al., 2020). Human-induced changes pose significant threats to ecosystem functionality and species interactions (Carugati et al., 2018).

Pongok Island stands out as a remarkable example of effective mangrove conservation, having recorded an increase of approximately 275.76 hectares, or 5.82%, in its primary mangrove forests (Table 3 and Figure 4). This growth highlights the success of restoration efforts and habitat protection initiatives. Primary mangrove forests are vital for providing essential ecosystem services, such as carbon sequestration, serving as nursery habitats for marine life, and offering protection to coastal areas (Miller and Tonoto, 2023). They have the capacity to sequester significantly more carbon than tropical terrestrial forests, highlighting their crucial role in biodiversity conservation and climate change mitigation through blue carbon storage (Alongi, 2020; Taillardat et al., 2018).

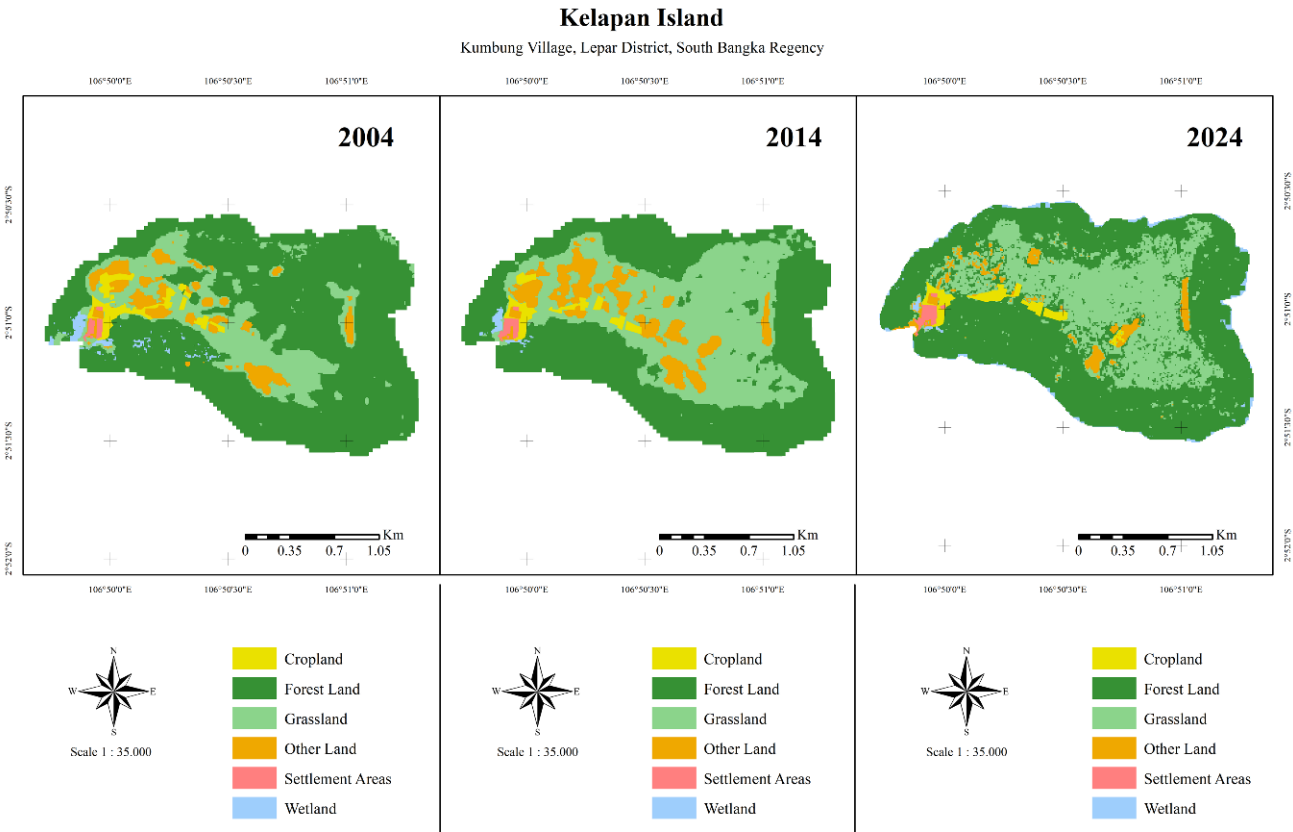


Figure 3. LULC changes in Kelapan Island for the years 2004, 2014, and 2024

Table 3. Changes to the LULC classification of Pongok Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	6.39	0.13	14.30	0.30	178.84	3.72	+172.45	+3.59
Forest land	Primary mangrove forest	1,436.74	29.81	1,671.71	34.66	1,712.50	35.64	+275.76	+5.82
	Secondary dryland forest	183.86	3.82	119.43	2.48	220.75	4.59	+36.89	+0.78
	Secondary mangrove forest	62.94	1.31	55.00	1.14	4.26	0.09	-58.68	-1.22
Grassland	Wet shrubland	2,477.78	51.42	2,168.23	44.96	1,923.89	40.04	-553.90	-11.38
Other land	Bare ground	588.57	12.21	663.82	13.77	660.15	13.74	+71.58	+1.52
Settlement areas	Settlement areas	36.51	0.76	42.88	0.89	43.33	0.90	+6.82	+0.14
Wetland	Swamp	9.41	0.20	41.64	0.86	14.16	0.29	+4.75	+0.10
	Water bodies	16.66	0.35	45.48	0.94	47.19	0.98	+30.53	+0.64
Total area (ha)		4,818.86		4,822.49		4,805.06			

Pongok Island has faced a notable decline in its secondary mangrove forests, with approximately 58.68 hectares, or 93.23%, lost. Although secondary mangroves hold less ecological value compared to primary forests, they remain essential for creating habitats and facilitating ecosystem recovery (Eddy et al., 2021). This reduction can be attributed to both natural processes and human activities, particularly illegal tin mining, which disrupts the ecological balance (Pratiwi et al., 2025). The concurrent 172.45-

hectare expansion of mixed dry agriculture reflects increasing economic pressures that must be balanced with conservation priorities (Musselli and Sonderegger, 2025).

The interplay between enhanced mangrove conservation and agricultural expansion raises vital questions for future landscape management. The idea that development and conservation can coexist with careful planning is worth exploring (Cameron et al., 2019; Saoum and Sarkar, 2024). While balancing

ecological preservation and economic growth presents significant challenges, successful navigation can yield sustainable benefits for both local communities (Alongi, 2020; Cameron et al., 2019). Pongok Island

illustrates this balance, showing gains in primary mangrove areas but declines in secondary forests, serving as both a success and a cautionary tale for long-term ecological stability.

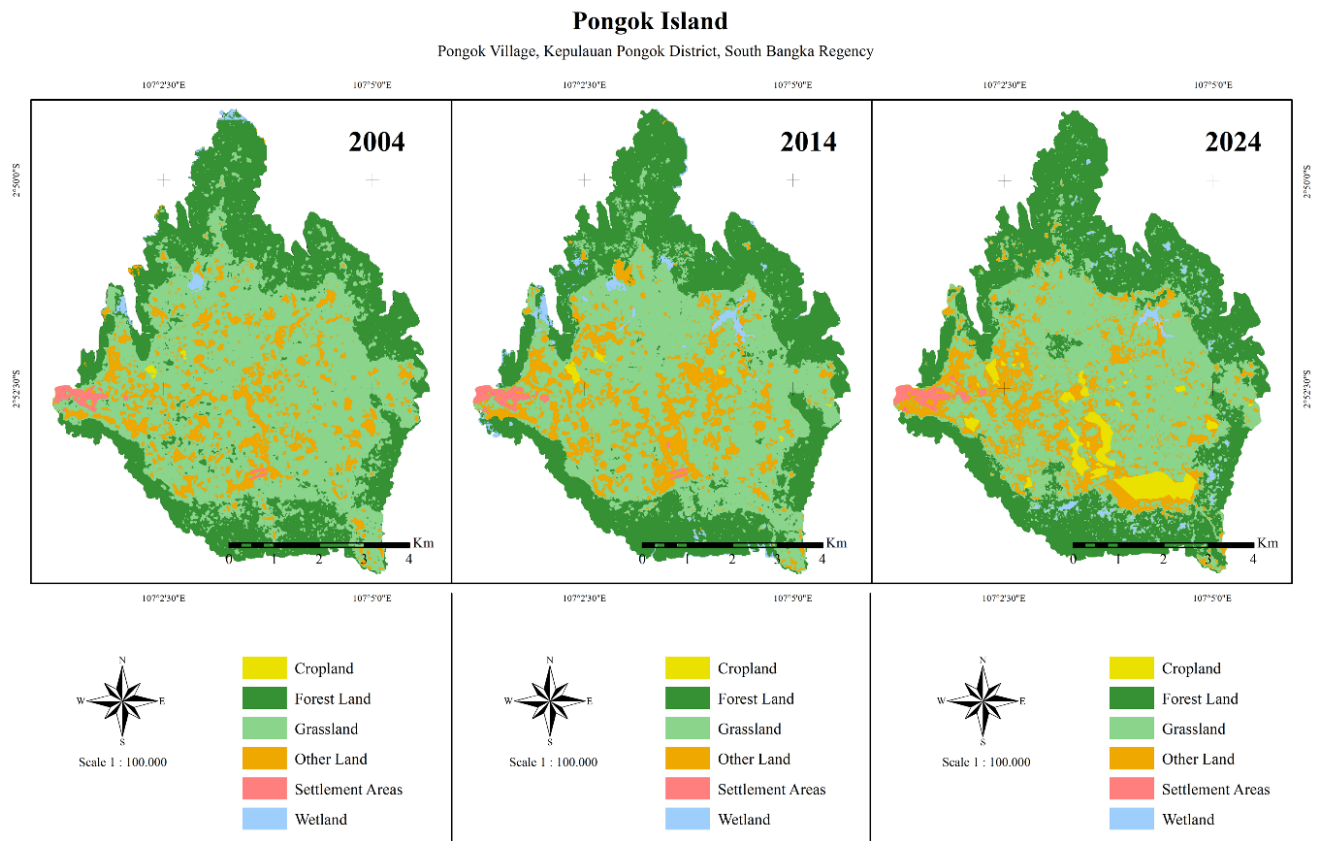


Figure 4. LULC changes in Pongok Island for the years 2004, 2014, and 2024

3.2 Biodiversity impacts and critical conservation thresholds

Landscape fragmentation analysis highlighted critical biodiversity thresholds (Tables 4 and 5). Kelapan Island experienced the most severe degradation, with a 29.5% decline in mean patch size and a 71.8% rise in edge density. Forest connectivity dropped to “very low” levels, indicating a high risk of species isolation. In contrast, Tinggi Island maintained a “medium-high” level of connectivity despite disturbances from mining. Pongok Island successfully preserved “high” connectivity while accommodating agricultural expansion.

Tinggi Island exhibits controlled fragmentation, with only three patches (7.1%) undergoing change over a two-decade period. This stability in patch numbers indicates that land-clearing is well-distributed, which is vital for species requiring moderate habitat. Research underscores the

importance of patch stability for biodiversity conservation in fragmented landscapes (Fahrig, 2017; Yan et al., 2023). The observed decline of 6.5% in mean patch size suggests that, while fragmentation has occurred, it remains within manageable thresholds that most species can endure (Fahrig, 2017).

Furthermore, the 13.3% increase in edge density indicates a greater interface of habitat disturbance, which may subject species to ecological stress. According to the edge effects theory, conditions at habitat edges can significantly differ from those in the interior. These disparities may lead to heightened predation risk, fluctuations in humidity, and increased exposure to radiation (Reek et al., 2025). Importantly, while these changes are still within moderate ranges that can be addressed through targeted conservation efforts, the implications for species adapted to interior habitats must be carefully evaluated (Gaines et al., 2022).

Table 4. Major LULC changes by island (2004-2024)

Island	Change type	Area (ha)	Change (%)	Driver	Impact assessment
Tinggi	Forest regeneration	+18.26	+5.68	Natural succession, conservation	Positive conservation outcome
	Wetland expansion	+24.48	+7.74	Illegal tin mining activities, water-filled pits	Environmental degradation concern
	Cropland expansion	+7.28	+37.69	Agricultural intensification	Moderate agricultural pressure
	Secondary mangrove → Wetland	-4.48	-1.42	Natural tidal conversion + mining impacts	Mixed natural-anthropogenic process
Kelapan	Forest loss (net)	-38.1	-9.97	Land clearing for clove plantations and selective logging	Requires conservation intervention
	Secondary dryland → Grassland	-35.2	-19.05	Forest clearing for clove cultivation and grazing	Major habitat conversion
	Grassland expansion	+47.43	+12.31	Land clearing result, temporary grazing before clove planting	Landscape fragmentation
	Clove plantation development	+15.8	+22.16	New clove plantation establishment	Economic diversification
	Wetland dynamics	+2.31	+0.60	Variable tidal patterns	Coastal instability
Pongok	Forest regeneration (net)	+253.97	+5.38	Conservation efforts, natural recovery	Major conservation success
	Primary mangrove expansion	+275.76	+5.82	Restoration programs, protection efforts	Blue carbon enhancement
	Cropland expansion	+172.45	+3.59	Large-scale agricultural development, new rice fields	Major economic development
	Secondary mangrove → Wetland	-58.68	-1.22	Natural conversion + small-scale illegal tin mining (<i>kolong</i>)	Mixed natural-anthropogenic process
	Grassland → Forest conversion	+36.89	+1.49	Secondary succession, reforestation	Natural regeneration success
	Small-scale mining impacts	~5.20	~0.11	Illegal tin mining activities, localized <i>kolong</i> formation	Environmental monitoring needed

Table 5. Landscape fragmentation and biodiversity impact assessment

Island	Metric	2004	2014	2024	Change absolute	Change (%)	Biodiversity impact
Tinggi	Number of patches	42	48	45	+3	+7.1	Moderate fragmentation
	Mean patch size (ha)	7.52	6.59	7.03	-0.49	-6.5	Moderate habitat reduction
	Edge density (m/ha)	27.8	33.2	31.5	+3.7	+13.3	Mining-induced edge effects
	Shannon diversity index	1.32	1.45	1.48	+0.16	+12.1	Increased landscape diversity
	Forest connectivity	High	Medium	Medium-high	Recovery	-	Improving with regeneration
Kelapan	Number of patches	55	72	78	+23	+41.8	High fragmentation
	Mean patch size (ha)	6.99	5.34	4.93	-2.06	-29.5	Significant habitat loss
	Edge density (m/ha)	24.5	36.8	42.1	+17.6	+71.8	Severe edge effects
	Shannon diversity index	1.25	1.38	1.52	+0.27	+21.6	Diversity from fragmentation
	Forest connectivity	Medium	Low	Very low	Critical decline	-	High species isolation
Pongok	Number of patches	195	215	228	+33	+16.9	Controlled fragmentation
	Mean patch size (ha)	24.71	22.43	21.07	-3.64	-14.7	Manageable patch reduction
	Edge density (m/ha)	11.8	14.5	16.2	+4.4	+37.3	Moderate edge increase
	Shannon diversity index	1.18	1.32	1.41	+0.23	+19.5	Positive diversity increase
	Forest connectivity	High	High	High	Maintained	-	Conservation success

Kelapan Island displays concerning patterns of fragmentation that exceed critical conservation thresholds. The 41.8% increase in the number of patches indicates unplanned fragmentation resulting

from land clearing, which undermines ecosystem integrity (Wintle et al., 2018). The 29.5% decline in mean patch size signals a serious warning regarding habitat degradation, as many species require specific

areas to thrive (Saravia et al., 2018). Furthermore, the 71.8% increase in edge density signifies a substantial structural change in the landscape, which may impact sensitive species, including large mammals and moisture-dependent amphibians (Fahrig, 2017).

Although the 21.6% rise in the Shannon diversity index may initially appear encouraging, it presents a paradox in which increased diversity correlates with fragmentation, thereby jeopardising the integrity of core habitats (Saravia et al., 2018). The marked decline in forest connectivity further restricts species movement, elevating their risk of extinction (Lindenmayer, 2023). These trends suggest that Kelapan Island's ecosystem may be approaching irreversible degradation without timely intervention (Saravia et al., 2018).

Pongok Island exemplifies notable conservation success by maintaining high levels of connectivity amid significant land-use changes. The moderate 16.9% increase in the number of patches (rising from 33 to 39) suggests a more structured form of fragmentation compared to Kelapan Island (Fahrig, 2017). Meanwhile, the 14.7% decline in mean patch size indicates a less severe impact, allowing for substantial habitat patches to remain intact. The 37.3% rise in edge density, while significant, is lower than that observed on Kelapan Island, reflecting more controlled landscape transformations (Timmers et al., 2025).

Furthermore, a 19.5% increase in the Shannon diversity index signifies adequate land-use diversification, balancing agricultural development with the preservation of connected forest areas. This high connectivity, bolstered by sound land management practices, enhances species movement and ecosystem resilience (Li et al., 2024). Consequently, Pongok Island's approach may exemplify land-sparing strategies by keeping agricultural and conservation areas distinct, thus preserving ecological integrity in the face of development pressures and serving as a model for tropical coastal regions (Lacambra et al., 2024).

3.3 Effectiveness of land-use management policies

Current regulations, including the Regulation of the Provincial Government of the Bangka Belitung Islands Province No. 3/2020, about the Zoning Plan for Coastal Areas and Small Islands, along with the Regulation of South Bangka Regency No. 6/2014, which outlines the Spatial Plan for South Bangka Regency. Regulatory gaps between marine and

terrestrial governance frameworks have facilitated unregulated illegal mining and deforestation activities across all islands.

The regulatory failures across all three islands reveal a fundamental mismatch between governance structures and landscape-scale processes (Gunawan et al., 2024b; Setiawati et al., 2023). Marine-focused regulations inadequately address the drivers of terrestrial transformation, creating enforcement gaps that enable destructive activities (Tolessa et al., 2021; Dastour and Hassan, 2023). The upcoming Government Regulation No. 27/2025 on Mangrove Ecosystem Protection presents an opportunity to bridge these governance gaps through integrated coastal-terrestrial management frameworks (Mashala et al., 2023).

These findings have immediate implications for the hundreds of similar small islands across Indonesia and other archipelagic nations (Kelman, 2018; Révillion et al., 2019). The 20-hectare threshold and connectivity requirements provide concrete targets for conservation planning (Loos et al., 2015), while the Pongok Island model illustrates viable pathways for balancing development with ecosystem integrity (Reksa et al., 2021; Rimmer et al., 2021). The regulatory lessons emphasize the urgent need for governance frameworks aligned with the scale and complexity of small island socio-ecological systems (Lennert et al., 2020; Yetein et al., 2025).

Preserving biodiversity on small islands is crucial to maintaining habitat patch sizes of at least 20 hectares and ensuring high connectivity to prevent species isolation and local extinction. The conditions of the islands highlight this need: Kelapan has suffered significant degradation due to low connectivity, while Pongok demonstrates that mangrove expansion (approximately 275.76 hectares) can occur alongside agricultural growth with proper protection. The Provincial Government should lead in integrating land-sea governance by aligning spatial plans and coastal zoning, incorporating the "≥20 ha + connectivity" criterion into environmental licensing, and implementing effective monitoring and reporting systems to fill enforcement gaps.

4. CONCLUSION

This 20-year analysis of land use on small inhabited islands in South Bangka, Indonesia, reveals three transformation patterns influenced by human activities and natural processes. Tinggi Island shows forest resilience despite illegal tin mining, while

Kelapan Island faces severe ecological degradation and habitat fragmentation, prompting urgent conservation measures. In contrast, Pongok Island has successfully expanded its mangrove ecosystems despite the intensification of agriculture. A biodiversity impact assessment emphasizes the importance of maintaining patch sizes over 20 hectares and ensuring connectivity for species persistence. Current land-use management policies are ineffective due to a disconnect between marine and terrestrial governance, highlighting the need for integrated conservation strategies that balance development with ecosystem integrity. This research offers evidence-based recommendations for sustainable land-use planning and conservation.

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AUTHOR CONTRIBUTIONS

Henri conceptualised and methodologically carried out data collection and analysis, and drafted and revised the manuscript. Luchman Hakim, Catur Retnaningdyah, and Brian Rahardi contributed equally through supervision, critical review, and manuscript revision.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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Modeling Land-Use Transitions under Conflicting Conservation and Land Tax Policies in Bang Kachao, Thailand

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ABSTRACT

Bang Kachao Subdistrict faces a policy conflict between the 2019 conservation zoning regulation, which mandates at least 25% green cover, and the Land and Buildings Tax Act in 2019, which progressively increases idle land tax rates from 0.5% to 3% within three years. The rising tax burden has accelerated land conversion from vacant and forested plots to monoculture farms, threatening local ecosystem integrity. Using high-resolution drone imagery and high-resolution satellite imagery obtained from Google Earth Pro for the year 2005 and 2015, six land-use classes were mapped and projected to 2045. The model achieved an overall accuracy of 89.7% (Kappa = 0.86), forecasting a 14.1% decline in forest area (-0.144 km²), 15.9% agricultural net increase (+0.185 km²), and an increase in idle land from 0.031 km² to 0.094 km² over the 40-year period. Field surveys confirmed that landowners replaced nipa palm wetlands with eucalyptus plantations to qualify for tax exemptions. These results indicate that progressive taxation can undermine conservation policies. It is recommended that subdistrict governors establish Memoranda of Understanding (MOUs) with landowners to support nipa palm and native forest restoration through capped tax rates and integrated land-use zoning.

HIGHLIGHTS

- Modeled land-use in Bang Kachao under conflicting tax and conservation policies.
- High-resolution drone and satellite data projected a 14.1% forest decline by 2045.
- Progressive land taxes drive conversion of native wetlands to monoculture farms.
- Proposed MOUs and tax caps to align fiscal policy with ecological preservation.

1. INTRODUCTION

Land-use and land-cover (LULC) dynamics are central to understanding ecological balance, resource distribution, and human well-being, as changes in LULC significantly influence biodiversity, hydrological cycles, and greenhouse gas emissions (Liu et al., 2020; Khan et al., 2023). Land cover refers to the physical characteristics of the Earth's surface, such as forests, croplands, or urban areas, whereas land-use reflects the human activities that modify these features. Globally, rapid urbanization and agricultural expansion have intensified these transformations, raising concerns about the long-term resilience of peri-urban ecosystems. Bang Kachao, located in Phra

Pradaeng District, Samut Prakan Province, and widely recognized as the “green lung” of Bangkok, which it exemplifies these tensions between conservation and development (Yotapakdee et al., 2018). In 2019, the Thai government declared Bang Kachao an environmental protection area, mandating that at least 25% of the area remain as green space and restricting construction across six subdistricts (Saksornchai, 2019). However, the Land and Buildings Tax Act of 2019, enacted in 2020, imposes escalating taxes on idle land, rising from 0.5% in the first year to 3% after three years, incentivizing landowners to convert vacant plots into ecologically simplified monoculture plantations, such as banana, mango, or

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coconut, to reduce tax liability (Nanakorn, 2019). The interaction between conservation zoning and fiscal policy thus generates contradictory incentives, distinguishing Bang Kachao from other regional contexts. Whereas Jakarta's progressive land tax aims to reduce speculative land hoarding (Apriani and Inayati, 2020), in Bang Kachao economic pressure instead drives ecological change by encouraging the clearance of natural vegetation to qualify for lower tax rates. Consequently, the policy landscape serves as a laboratory for examining how overlapping legal and fiscal instruments shape land-use decisions.

This situation also exposes conceptual ambiguities in how "green space" is defined. In urban planning, agricultural areas are often counted toward green space quotas ($\geq 25\%$), yet ecologists argue this practice overestimates ecological health (Taylor and Hochuli, 2017). Agricultural monocultures, despite appearing "green," frequently rely on chemical inputs that degrade soil, water, and biodiversity (Raven and Wagner, 2021; Zhao et al., 2024; Jing et al., 2025). A function-based definition restricting "green space" to areas providing net positive ecosystem services such as native forests or low-impact agroforestry is therefore more appropriate for sustainability assessment. While the biophysical and spatial drivers of LULC change have been widely studied (Orina et al., 2024), socio-legal mechanisms, particularly taxation remain underexplored. Fiscal instruments can promote efficient land-use, but their environmental impact depends on governance capacity and policy design (Kalkuhl et al., 2017). This study addresses this research gap by examining how progressive taxation interacts with conservation policy to shape peri-urban land dynamics in Bang Kachao.

The central hypothesis is that progressive tax escalation under Thailand's land taxation framework may override conservation rules, thus accelerating the conversion of idle and wetland forests into low-diversity agricultural land and contributing to net forest loss. Accordingly, this study pursues three main objectives. First, it aims to assess and forecast land-use and land-cover (LULC) changes following the implementation of conservation zoning and the Land and Buildings Tax Act. To achieve this, an artificial neural network-based Multi-Layer Perceptron (ANN-MLP) modeling framework is employed to simulate land-use trajectories for the years 2035 and 2045. Second, the study seeks to verify the accuracy of the model by comparing simulated outcomes with observed data, ensuring the robustness and reliability

of the projections. Finally, the study aims to propose policy recommendations to support informed decision-making by local authorities and landowners navigating conflicting regulatory pressures between fiscal policies and conservation mandates. Through this analysis, Bang Kachao serves as a case study of how fiscal and ecological governance intersect, offering broader insights for rapidly urbanizing regions seeking to reconcile conservation objectives with economic and social imperatives.

2. METHODOLOGY

This study employed a mixed-method approach integrating quantitative LULC modeling with qualitative stakeholder insights. The Artificial Neural Network-Cellular Automata (ANN-CA) model quantified spatial change and forecasted future scenarios, while focus group discussions and on-site surveys provided contextual understanding of land management decisions and tax compliance behavior.

2.1 Study area

Bang Kachao is a conserved green area covering approximately 16 km² across six subdistricts in Phra Pradaeng District, Samut Prakan Province, Thailand (approximately 13.6°N, 100.6°E). This study focuses on Bang Kachao Subdistrict, which forms part of the larger Bang Kachao Area and covers approximately 3.14 km² (Figure 1).

2.2 Data sources and LULC modeling

Historical satellite imagery from Google Earth Pro in 2005 and 2015 was used to assess long-term land-use and land-cover (LULC) transitions in Bang Kachao Subdistrict before and after major policy interventions of the 2019 conservation zoning and the 2020 Land and Buildings Tax Act. All images were visually interpreted and cross-validated against the 2025 UAV orthomosaic and local land records to ensure temporal consistency. Concurrent field surveys of ten purposively selected landowner properties provided additional ground verification through GPS-referenced photos and site observations. Although Google Earth Pro offers high-resolution visualization, its lack of standardized spectral data and acquisition metadata introduces minor uncertainties (Bol and Randhir, 2024). Consequently, the analysis emphasizes relative temporal trends such as forest reduction and urban expansion rather than exact area estimates, ensuring robustness and reproducibility.

2.2.1 UAV data acquisition and orthophoto processing

High-resolution aerial imagery of Bang Kachao Subdistrict was captured using an MX1000 Multirotor drone with an RTK Station Emlid RS2 between 21 and 22 January 2025 under clear weather conditions (Torres et al., 2024). The survey produced

overlapping photographs processed through Agisoft Metashape (Agisoft LLC, 2022) and ArcMap 10.8 (Esri, 2020) to generate a georeferenced orthomosaic with ≈ 3 cm spatial resolution (Tripathi et al., 2024). Accuracy was validated with 107 ground control points following established photogrammetric procedures (Kögel et al., 2025).

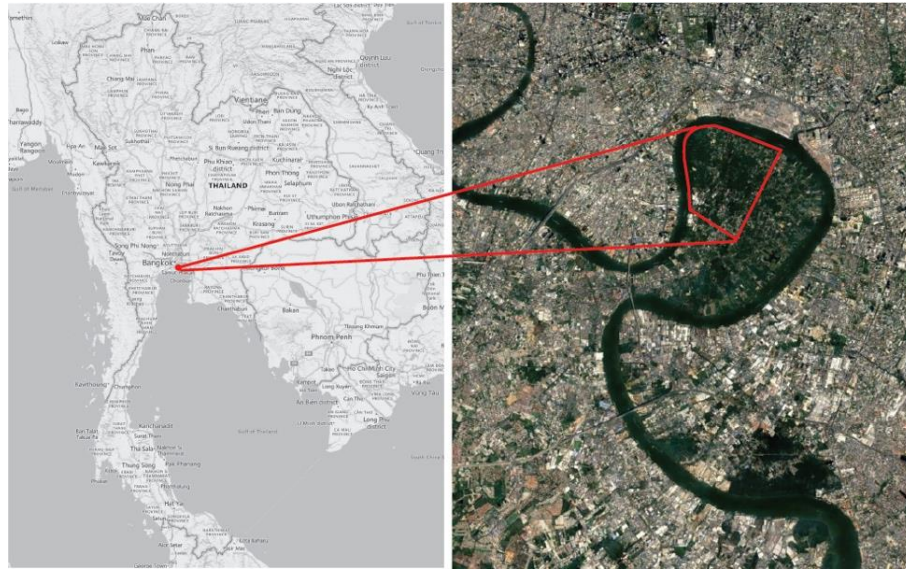


Figure 1. Satellite image of Bang Kachao Subdistrict, Samut Prakan Province, Thailand (source: Google Earth Pro).

2.2.2 Land-use and land-cover classification

LULC classification was designed to represent both ecological and socio-economic characteristics of the peri-urban landscape. Six categories were delineated from field observations, UAV orthophotos, and historical imagery: (i) agricultural land, (ii) forest land, (iii) urban and built-up land, (iv) idle land, (v) water body, and (vi) canals in agricultural areas. The canal category was distinguished separately because canal siltation often signals farmland abandonment. This classification framework supports spatial analysis of environmental change and quantification of land-use transitions, clarifying how policy pressures and hydrological factors shape Bang Kachao's landscape transformation.

2.2.3 LULC modeling and forecasting

The workflow comprised three main stages: data acquisition, processing and digitization, and change detection with calibration and forecasting (Figure 2). All imagery was imported into QGIS, georeferenced to the 2025 UAV orthophotos, and digitized through heads-up interpretation to delineate six LULC classes agricultural land, forest land,

urban/built-up land, idle land, water bodies, and canals in agricultural areas (Zhang et al., 2022). Vector polygons were assigned class codes and converted into classified raster layers with consistent spatial resolution and coordinate projection. These standardized raster datasets were then used for calibration and simulation within the Modules for Land-Use Change Evaluation (MOLUSCE) environment implemented in QGIS (NextGIS, 2019; Albut, 2024).

To enable modeling, digitized vector polygons were rasterized at a uniform 3 m spatial resolution (3 meter $\times$ 3 meter area on the ground) using Universal Transverse Mercator-UTM Zone 47N projection. This process preserved boundary precision while standardizing inputs for transition analysis. Rasterized LULC maps for 2005, 2015, and 2025 were paired with explanatory variables representing proximity to roads, canals, and water bodies, as well as spatial neighborhood effects within a 3×3 cell window. These driving factors were derived from validated UAV and satellite data to capture both physical and policy-driven forces influencing land-use transitions.

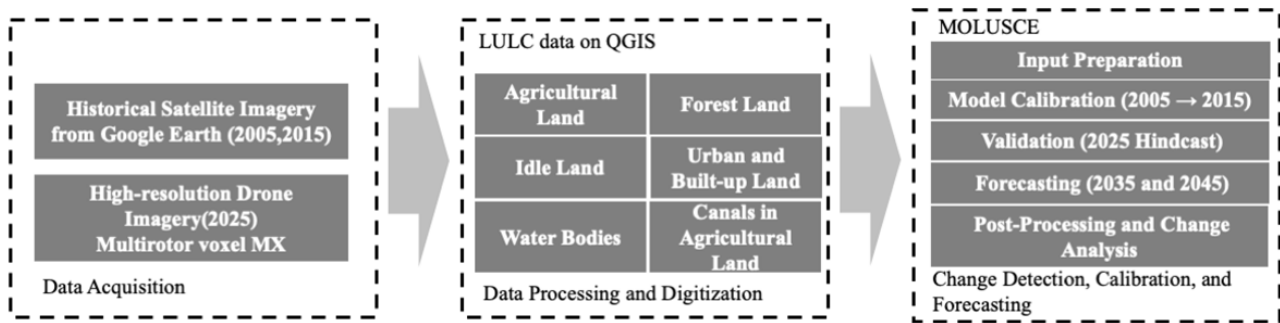


Figure 2. Workflow of data acquisition, processing, and forecasting of LULC changes.

2.2 Focus group

The focus group activities were conducted in Bang Kachao Subdistrict, involving local farmers, homestay operators, municipal officials, and community leaders. Two sessions were organized to gather stakeholder perspectives on future land-use scenarios. During the first focus group, participants were presented with drone-derived maps and field survey data to facilitate discussion on current land-use patterns and their perceived changes. They were asked to reflect on possible future scenarios for Bang Kachao considering ongoing environmental and policy pressures. The second focus group was structured as a participatory workshop focused on land-use design under the Land and Buildings Tax Act in 2019. Participants were tasked with developing land-use models that balance economic returns, environmental sustainability, and community well-being. This exercise encouraged local stakeholders to envision adaptive management strategies aligned with both fiscal and ecological objectives. Additionally, participants conducted an exercise to calculate the break-even point between investment in land development and tax exemption.

3. RESULTS AND DISCUSSION

3.1 Land-use and land-cover

Figure 3 illustrates the land-use and land cover (LULC) patterns of Bang Kachao Subdistrict in 2025, derived from UAV-based orthophotos. Agricultural land occupies the largest proportion of the area (Figure 3(a)), reflecting the persistence of fruit orchards and small-scale household cultivation. Forest land is the second most extensive category and can be divided into two main types: wetland forest dominated by nipa palm (*Nypa fruticans* Wurmb) along the western riverbank adjacent to the Chao Phraya River, and mixed dry forest located in the interior (Figure 3(b)). Urban and built-up areas are concentrated in the

central part of the subdistrict, corresponding to the main road network and settlement clusters (Figure 3(c)). Idle land represents the smallest category and is typically found along road corridors, indicating plots awaiting future development (Figure 3(d)). The subdistrict contains twelve main canals connecting inland areas to the Chao Phraya River (Figure 3(e)), along with numerous smaller canals dispersed throughout agricultural zones (Figure 3(f)). As can be seen, the forest in the northern part has a smaller extent than that in the east due to road accessibility. Where roads are present, the area has the potential to become urban, leading to a reduction in forest area. Additionally, agricultural areas have interspersed with forest land, which may have implications for biodiversity. This aspect warrants further investigation.

3.2 Class-by-class change

The transition probability matrix (Table 1) was calibrated using observed LULC changes from 2015 (pre-tax) to 2025 (post-tax), reflecting land-use dynamics during the first decade following the implementation of the Land and Buildings Tax Act in 2019 (effective from 2020).

The analysis revealed high stability across most land-use types in Bang Kachao Subdistrict. Water bodies and idle land remained completely stable (probability of persistence for each land-use type, $p=1.000$), indicating that during the first decade following the implementation of the 2019 Land and Buildings Tax (effective in 2020), the tax had little to no observable impact on reducing idle land. Urban and built-up land ($p=0.993$) and agricultural land ($p=0.996$) also showed high persistence, indicating relative stability of both developed and agricultural areas during the first decade, which may be influenced by policy mechanisms such as the Land and Buildings Tax Act. Forest land exhibited moderate stability

($p=0.959$), with minor losses primarily to agricultural land ($p=0.024$) and idle land ($p=0.012$). In contrast, canals in agricultural areas were the least stable ($p=0.749$), with 21.0% converting to agricultural land and 1.7% to urban and built-up land. This loss was not

directly driven by tax policy but rather by farmer abandonment associated with soil salinity, a common biophysical stressor in deltaic environments that intensifies as productivity declines.

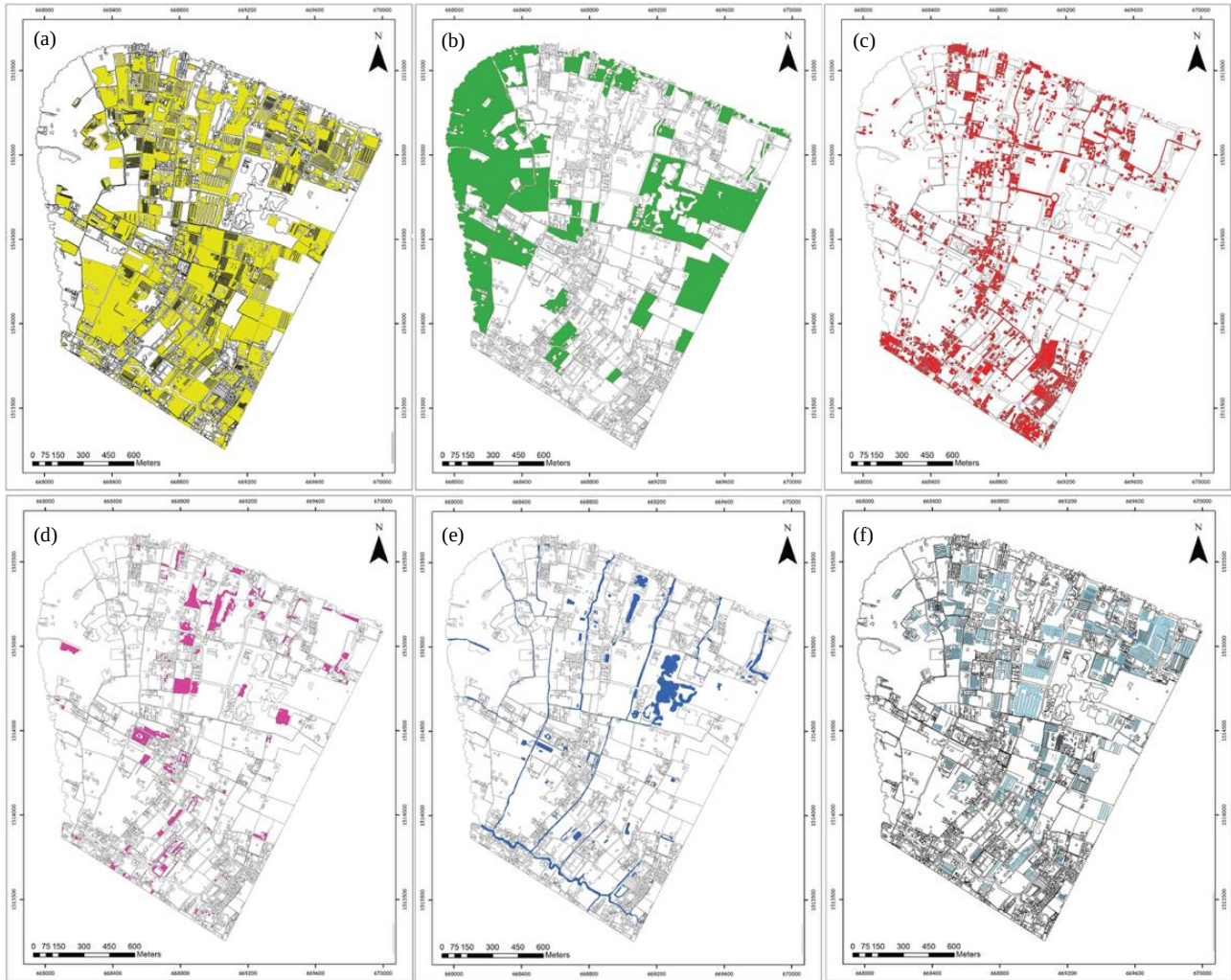


Figure 3. Land-use classification on (a) Agricultural Land, (b) Forest Land, (c) Urban/Built-up Land, (d) Idle Land, (e) Water Body, (f) Canals in Agricultural Areas in year 2025

Table 1. Land-use and land-cover transition probability matrix LULC from 2015 to 2025

LULC	Water body	Idle land	Forest land	Urban and built-up Land	Agricultural land	Canals in agricultural area
Water body	1.000	0.000	0.000	0.000	0.000	0.000
Idle land	0.000	1.000	0.000	0.000	0.000	0.000
Forest land	0.001	0.012	0.959	0.003	0.024	0.001
Urban and built-up land	0.000	0.002	0.004	0.993	0.003	0.002
Agricultural land	0.009	0.003	0.000	0.000	0.996	0.000
Canals in agricultural area	0.007	0.014	0.003	0.017	0.210	0.749

Table 2 presents temporal changes in land-use and land cover (LULC) in Bang Kachao Subdistrict from 2005 to 2045. Agricultural Land remains the dominant category, showing a net increase from 1.23 km² to 1.36 km² ($\pm 4.13\%$). Forest Land shows a steady decline (-0.198 km², or -6.31%), while Canals in Agricultural Areas decrease (-0.093 km², or -6.31%), indicating the degradation of the ditch network due to the abandonment of agricultural land. Urban and Built-up Land expands ($+0.085$ km², or $+2.71\%$) and stabilizes after 2025. Idle

Land increases ($+0.060$ km²) due to abandonment of marginal plots. Water Body area remains stable, reflecting relative hydrological resilience. The model's intermediate projection for 2035 aligns closely with the 2025 UAV observations, confirming temporal robustness for the 2045 forecast. Overall, the results illustrate a gradual transition from forest and canal-based landscapes toward more intensively cultivated and urbanized forms, driven by fiscal pressure and environmental challenges.

Table 2. Land-use and land-cover (LULC) change in Bang Kachao subdistrict, 2005-2045

LULC category	2005 (km ²)	2015 (km ²)	2025 (km ²)	2035 (km ²)	2045 (km ²)	Δ Area (km ² , 2005-2045)	Δ (%)
Water body	0.131	0.124	0.149	0.148	0.148	+0.017	+0.54
Idle land	0.034	0.050	0.113	0.096	0.094	+0.060	+1.91
Forest land	1.082	0.971	0.886	0.844	0.884	-0.198	-6.31
Urban and built-up land	0.373	0.339	0.461	0.459	0.458	+0.085	+2.71
Agricultural land	1.230	1.407	1.329	1.354	1.360	+0.130	+4.13
Canals in agricultural area	0.292	0.261	0.204	0.201	0.199	-0.093	-2.96
Total area	3.142	3.142	3.142	3.142	3.142	-	-

Figure 4 illustrates the temporal evolution of land-use and land-cover (LULC) from 2005 to 2035. In 2005 (**Figure 4(a)**), the landscape was primarily composed of agricultural and forest land, with scattered idle and limited urban areas. By 2015 (**Figure 4(b)**), forest areas declined and urban land slightly expanded, particularly along the northern and western boundaries, while agricultural land remained dominant but increasingly fragmented. The 2025 UAV orthomosaic (**Figure 4(c)**) reveals further agricultural encroachment into former forest zones, accompanied by reduced idle land and gradual urban growth. The 2035 ANN-CA simulation (**Figure 4(d)**) projects forest decline, agricultural expansion, and a sharp decrease in idle land, reflecting the influence of the 2019 Land and Buildings Tax Act, which discourages land underutilization. Overall, the sequence depicts a shift from forested to cultivated and developed land, emphasizing taxation and urbanization as key drivers of LULC transformation.

The graph illustrates the temporal evolution of land-use and land-cover (LULC) categories from 2005 to 2045, with areas measured in square kilometers ranging from approximately 0.12 km² to 1.40 km² (**Figure 5**). Six LULC classes Water Body, Idle Land, Forest, Urban and Built-up Area, Agricultural Land,

and Canals in Agricultural Area are represented by distinct lines with overlaid linear trend lines to indicate general temporal tendencies. Agricultural land increases from 1.162561 km² in 2005 to 1.347852 km² in 2045; however, the low coefficient of determination ($R^2=0.13$) indicates considerable temporal variability and suggests that this change is not well captured by a simple linear trend, likely reflecting non-linear and policy-driven land-use decisions associated with the Land and Buildings Tax Act. Forest land decreases consistently from 1.022286 km² to 0.878241 km², exhibiting a strong linear decline ($R^2=0.78$) that highlights ongoing conservation challenges.

Idle land increases to a peak of 0.112510 km² in 2025 before declining to 0.093646 km² in 2045, indicating a temporary rise followed by tax-induced land conversion ($R^2=0.62$). Urban and built-up areas remain relatively stable, reaching 0.458218 km² in 2025 and slightly decreasing to 0.455786 km² by 2045, with a moderate linear trend ($R^2=0.71$). Canals in agricultural areas show a strong and consistent decline from 0.276754 km² to 0.198273 km² ($R^2=0.80$), while water bodies remain largely stable, varying from 0.124632 km² in 2005 to 0.146900 km² in 2045 ($R^2=0.76$).

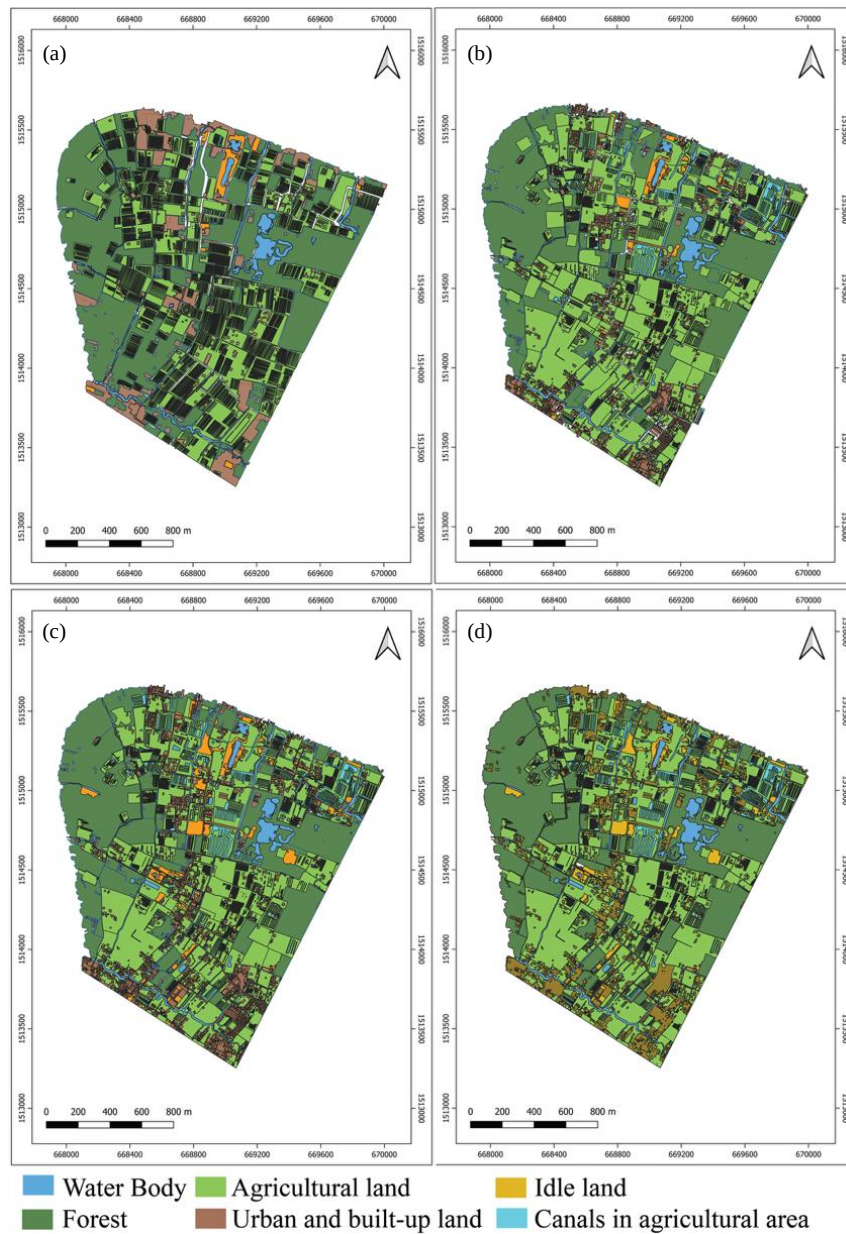


Figure 4. Simulated LULC change from 2005-2035: (a) 2005 baseline, (b) 2015, (c) 2025 UAV, (d) 2035 projection

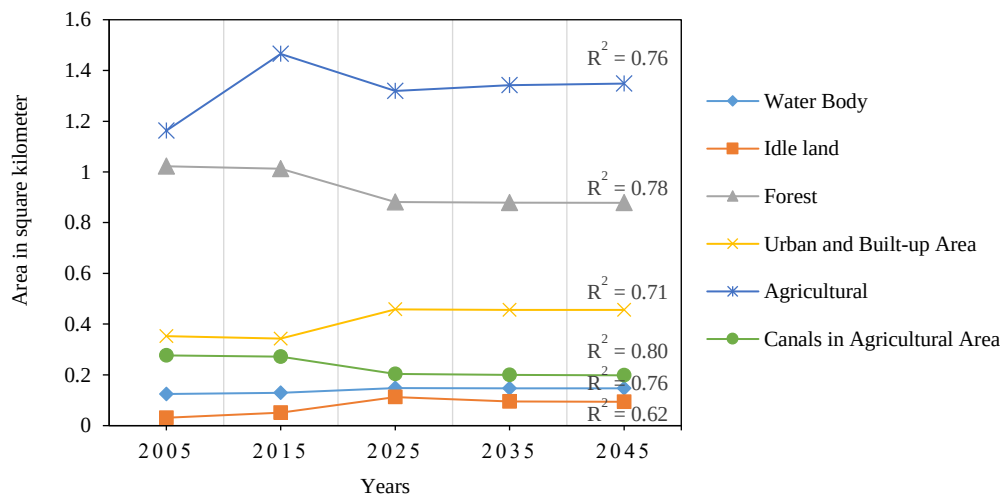


Figure 5. Temporal trends of land-use categories from 2005 to 2045

3.4 Validation

Figure 6 presents the multiple-resolution budget validation comparing observed and predicted 2025 LULC maps. The results indicate high overall agreement, with the medium location-medium quantity information curve consistently above 0.8 across resolutions, approaching the theoretical upper bound of perfect agreement. This demonstrates that the model performs well in balancing spatial allocation and land quantity predictions. By contrast, accuracy is lower when only quantity information is considered (approximately 0.35-0.4) and lowest under the no location-no quantity assumption (<0.25), underscoring the model's skill relative to chance. Performance improves modestly at coarser resolutions, suggesting that the model captures broader landscape patterns more effectively than fine-grained spatial details.

3.5 Site survey

Site surveys were conducted in April 2025 to qualitatively validate selected land-use and land-cover (LULC) transitions identified by the modeled LULC change analysis between 2023 and 2025. Ten land parcels were purposively selected from areas classified by the model as undergoing notable land-use change following the enforcement of the Land and

Buildings Tax Act. Among the surveyed parcels, eight were converted to coconut and mango farms, one to a garden house, and one to a learning center. One formerly residential parcel was converted to eucalyptus cultivation, and riverbank modifications, including the replacement of nipa palm with a stone barrier, were observed (Figure 7(a)). Another parcel originally classified as wetland dominated by nipa palm was completely cleared (Figure 7(b)). These site observations correspond to modeled transitions from residential or wetland categories to agricultural or developed land-uses. Although limited in number ($n=10$) and not statistically representative, the surveyed parcels provide illustrative case evidence that helps interpret policy-related LULC changes at the parcel level and complements the spatial modeling results.

These observations provide empirical evidence of land-use dynamics at the parcel level, demonstrating how policy-induced incentives translate into concrete transitions among residential, wetland, and agricultural land-uses. Analytically, these parcel-level responses suggest that land tax enforcement functions less as a deterrent to idle landholding and more as a catalyst for rapid, low-diversity land-use conversion, particularly in contexts where ecological land-uses lack clear fiscal recognition.

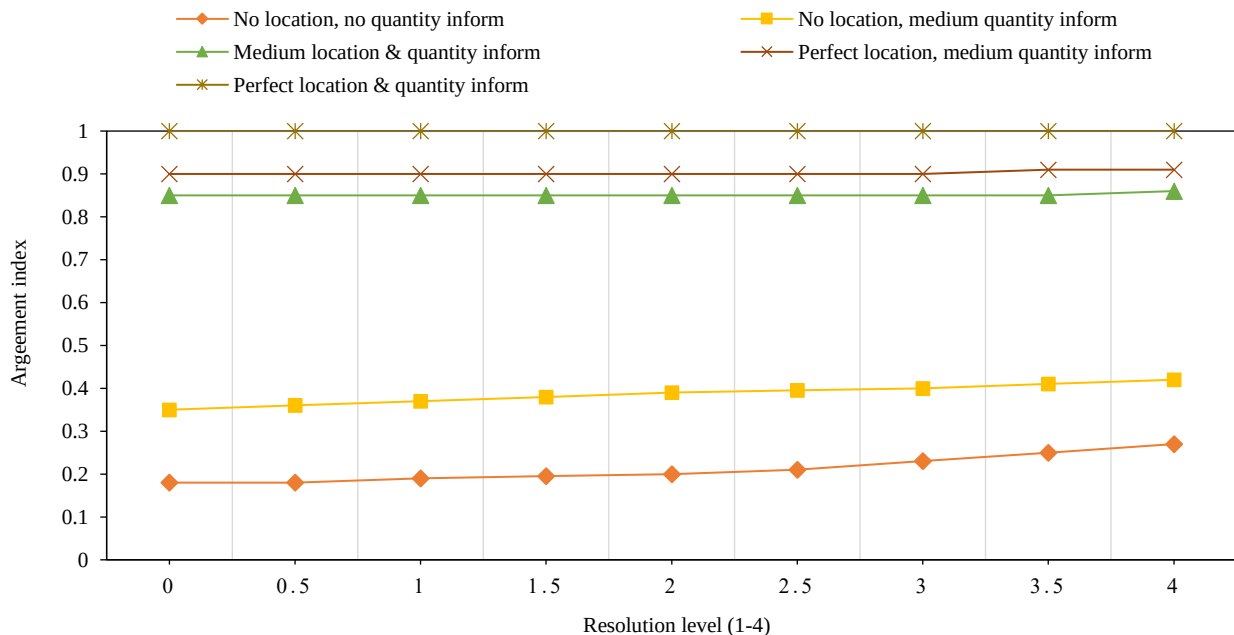


Figure 6. Multiscale validation of the 2025 LULC simulation using the Multiple-Resolution Budget (MRB) framework. Model agreement is decomposed into quantity agreement (correct total area per LULC class) and location agreement (correct spatial allocation). No location-no quantity represents a null baseline; no location-medium quantity indicates correct class proportions without spatial accuracy; medium location-medium quantity reflects partial agreement in both class amounts and spatial placement; perfect location-medium quantity represents ideal spatial allocation constrained by quantity errors; and perfect location-perfect quantity denotes the theoretical upper bound (Agreement Index=1.0), where simulated and observed maps are identical.



Figure 7. Land-use responses after implementation of the Land and Buildings Tax Act. (a) Landowners planting eucalyptus trees on previously idle land to avoid taxation; (b) Removal of nipa palm in wetland areas to convert land for taxable uses

Findings from a stakeholder workshop on tax-compliant, eco-friendly land design indicate that all landowners faced upfront compliance costs, contributing to six out of ten listing their land for sale by mid-2025. This suggests that conservation requirements, when paired with uncertain fiscal benefits, may unintentionally encourage land divestment. Focus group discussions further revealed legal ambiguity over whether nipa palm qualifies for tax exemption under the Mangrove Forest Conservation Act (2015). Although the Thai Cabinet has approved a land tax exemption for privately owned mangroves ([Department of Marine and Coastal Resources, 2024](#)), unclear implementation particularly for wetlands not formally classified as mangroves, creates policy misalignment. In line with SDG 15.a, this study recommends formal MOUs and tiered land tax relief (capped at 0.5%) for ecologically verified plots to reduce uncertainty, prevent land abandonment, and sustain ecosystem services. Together, these findings help explain the modeled land-use dynamics by showing how regulatory ambiguity and compliance costs translate into land divestment and subsequent land-use conversion.

According to the community leader, Bang Kachao frequently experiences soil salinity and farmland degradation, consistent with regional estuarine conditions reported by [Pokavanich and Guo \(2024\)](#). Since 2015, many agricultural plots have been abandoned or sold due to declining productivity and rising maintenance costs. Previous studies suggest that sustainable practices such as agroforestry and community-based forest management can improve soil health, biodiversity, and local livelihoods ([Mukul and Saha, 2017](#); [Alfonso-Bécares et al., 2024](#)). Encouraging these land-uses could restore ecological

balance and strengthen long-term economic resilience for landowners.

The expansion of non-native crops may be associated with reduced habitat suitability for native species, as simplified agricultural systems typically support lower biodiversity than natural or semi-natural vegetation ([BIOFIN, 2024](#)). However, this study does not directly measure biodiversity outcomes, and any ecological implications are inferred from observed land-use changes and existing policy assessments. Although forest loss in Bang Kachao remains limited, the observed trends highlight the importance of clear zoning that differentiates wetlands, agricultural areas, and settlements. Future research will incorporate field-based biodiversity surveys to test whether agricultural expansion and forest fragmentation are associated with measurable declines in species richness and ecological integrity.

4. CONCLUSION

Land-use forecasting in Bang Kachao Subdistrict indicates that progressive taxation under the Land and Buildings Tax Act (2019) has gradually overridden conservation zoning introduced the same year, contributing to continued forest decline and agricultural expansion projected through 2045. Although urban growth remains constrained, saline intrusion, unclear nipa palm classification, and high pond excavation costs have increased land divestment among local owners. These findings identify fiscal and regulatory uncertainty as key mechanisms limiting the mobilization of financial incentives required under SDG 15.a (Life on Land). In the short term, subdistrict authorities could clarify nipa palm classification and cap tax rates for ecologically verified forest and agroforestry areas to reduce immediate divestment

pressures. Over the longer term, structural reforms should align land-use taxation with conservation zoning and reinvest tax revenues in shared drainage and access infrastructure. Together, these measures would operationalize SDG 15.a by reducing land abandonment, strengthening wetland resilience, and promoting sustainable land management in Bang Kachao.

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AUTHOR CONTRIBUTIONS

Conceptualization, Phatworaruthai J, Teeravarunyou S; Methodology, Teeravarunyou S; Software, Kitirojpan P; Validation, Yao S; Formal Analysis, Torabi F; Investigation, Teeravarunyou S; Resources, Phatworaruthai J; Data Curation, Kitirojpan P; Writing-Original Draft Preparation, Teeravarunyou S; Writing-Review and Editing, Teeravarunyou S; Visualization, Yao S; Supervision, Pattanachan P; Project Administration, Kamolwit K; Funding Acquisition, Teeravarunyou S.

DECLARATION OF CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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Management Model for Rungan Watershed, Central Kalimantan, Indonesia: A Comprehensive Approach to Achieving Conservation and Community Development Goals

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ABSTRACT

The Rungan Watershed is facing an alarming rate of environmental degradation yet continuing to support the livelihoods of local communities. Therefore, this study is essential for addressing these issues and formulating adaptive management model. This research aims to assess environmental conditions and social economic aspects to formulate management model that is expected to serve as a framework for sustainable development in Palangka Raya City. By applying both qualitative and quantitative approaches, the study collects ecological, economic, and socio-cultural data to inform the development of management strategies. Land cover, land use, and vegetation density are assessed using remote sensing imagery and land cover maps. The analysis of forest vegetation density classes is conducted through the Normalized Difference Vegetation Index (NDVI), utilizing data from Landsat imagery. Socio-cultural information is gathered through interviews and observations. The study identifies various land cover condition, information on social economic condition that serve as a basis for developing a zoning based management model that categorizes the Rungan Watershed into conservation, buffer, and general utilization zones. This model accommodates the diverse interests of multiple stakeholders within a sustainable development framework. The study concludes that the zonation management of the sub-basin must align with the biophysical ecological conditions of the area, address existing challenges, and promote community welfare.

HIGHLIGHTS

This study employs a comprehensive approach to designing a management model for the Rungan Watershed, given the complexity of the challenges it faces. Ecological conditions, socio-economic factors, and cultural aspects are integrated to create a zoning management framework that accommodates the diverse interests of multiple stakeholders in support of sustainable development goals. The principles and approaches used in this research are applicable to land management worldwide under similar conditions.

1. INTRODUCTION

The future development direction of Central Kalimantan will focus on two key goals mandated by the central government: serving as a national food production centre and a world conservation center (Government of Central Kalimantan, 2024). To achieve this development vision, particularly the Smart Environment Vision, it is essential to maintain a diverse ecosystem, which plays a crucial role in enhancing the welfare of the city and the livelihoods

of its population. This approach aligns with efforts to meet sustainable development targets (Addai et al., 2023; Birkmann et al., 2022; Masot and Gascon, 2021).

The principle of sustainable development should also be applied in managing an area, particularly watersheds, to maintain a balance between biodiversity preservation and the optimal use of environmental services by prioritizing the active role of the community (Mengistu and Assefa, 2021; Narendra et al., 2021;

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Okiria et al., 2021; Shunglu et al., 2022). Essential ecosystem values, such as biodiversity, corridors for animal movement, and support for community livelihoods, must receive significant attention in development management design (Meena et al., 2022; Wang et al., 2023). This approach ensures that the environment can continue to support sustainable development (Ojelel et al., 2024). Watersheds in Central Kalimantan are vital to the region's ecosystem, as most of its ecosystems are shaped and influenced by rivers, therefore, formulating an adaptive management system of watershed is paramount.

Adaptive watershed management must consider the characteristics and uniqueness of each watershed to avoid damage and prevent broader environmental degradation. According to the latest watershed concepts formulated by experts, watersheds are understood not only as landscapes with topographic boundaries and hydrological unity but also as ecosystem units (Arnillas et al., 2021; Zhao and Huang, 2022). Watershed areas do not always align with specific administrative boundaries, often resulting in overlaps and conflicts of interest among various sectors. Therefore, integrated watershed management is necessary to achieve optimal conditions for the natural resources within these areas, ensuring that these resources can provide sustainable benefits for human welfare (Mosaffaie et al., 2021; Srivastav et al., 2021; Waskitho et al., 2021).

Apart from its significant role in supporting the environment and sustainable development, the Rungan watershed faces several environmental challenges. Traditional gold mining by local communities along the watershed leads to issues such as river pollution, damage to riparian areas, and disruption of fish habitats and life cycles. Additionally, deforestation and forest exploitation in the region contribute to the disturbance and fragmentation of wildlife habitats. Furthermore, its proximity to the city of Palangka Raya has further subjected the Rungan watershed to land cover changes for residential and infrastructure development.

The research related to river mostly focuses on one specific topic, for example, water erosion (Hagras, 2023), water pollution (Basuki et al., 2024; Ismanto et al., 2023), water quality (Marselina et al., 2022) and flooding (Hagras, 2025). Discussions about water management or watershed management generally focus on improving economic aspects and crop productivity (Hairani and Noor, 2020; Mainardis et al., 2022; Islam et al., 2022). Thus, research on water

management using a comprehensive approach remains limited.

Research on watershed management in Indonesia has highlight the importance of implementing sustainable watershed management. Supangat et al. (2023) discuss the importance of creating productive (Easter et al., 1985) and healthy watersheds through coordination and synchronization of programs among various related parties. This idea is based on the understanding that one of the main causes of watershed degradation is the lack of coordination between institutions and the pressure of anthropogenic activities. Basuki et al. (2024) argue that it is important to increase the integration of watershed management into climate change mitigation and adaptation efforts in Indonesia. Hairani and Noor (2020) specifically reviewed water management on peatlands for the purpose of agricultural and plantation development. They recommend combining technology and research results in managing water on peatlands to maintain ecological integrity while increasing agricultural productivity. Alhakim et al. (2025) studied the hydrological behavior of the Raya watershed in West Kalimantan in response to watershed characteristics. Various studies have also found that the government has implemented various program initiatives such as policy frameworks, institutional structures, and community-based management initiatives. However, these programs are considered unable to overcome the various obstacles faced by watershed management (Basuki et al., 2024; Narendra et al., 2021). The implementation of watershed management in Indonesia faces several major obstacles, such as a lack of program synchronization among stakeholders, bureaucratic confusion, and a lack of stakeholder participation, especially from the community, in the planning process (Narendra et al., 2021).

In response to these gaps and research needs, this study purposes a comprehensive approach by assessing land cover characteristics, collecting economic and social information from stakeholders, to develop an integrative and sustainable watershed management framework that synergizes program from different stakeholders in the Rungan Watershed. Integrative management planning can help implement strategic actions that promote environmentally friendly conservation and development efforts. This study adopts a comprehensive approach to develop a watershed management model, which has still been limitedly utilized in previous studies. The goal of this research is to establish priorities for the Rungan Sub-

Watershed management program, serving as a guideline for sustainable development in Palangka Raya City.

2. METHODOLOGY

The research applies a mix methods approach using qualitative and quantitative methods derived from the constructivist and positivist paradigms (Creswell, 2021).

2.1 Research location

The research was focused on the Rungan River Watershed in Palangka Raya Central Kalimantan Province, Indonesia (Figure 1). The research was carried out for five months, from January to May 2025 which including preliminary observation activities, preparation of research frameworks and tools, data collection, analysis and reporting.

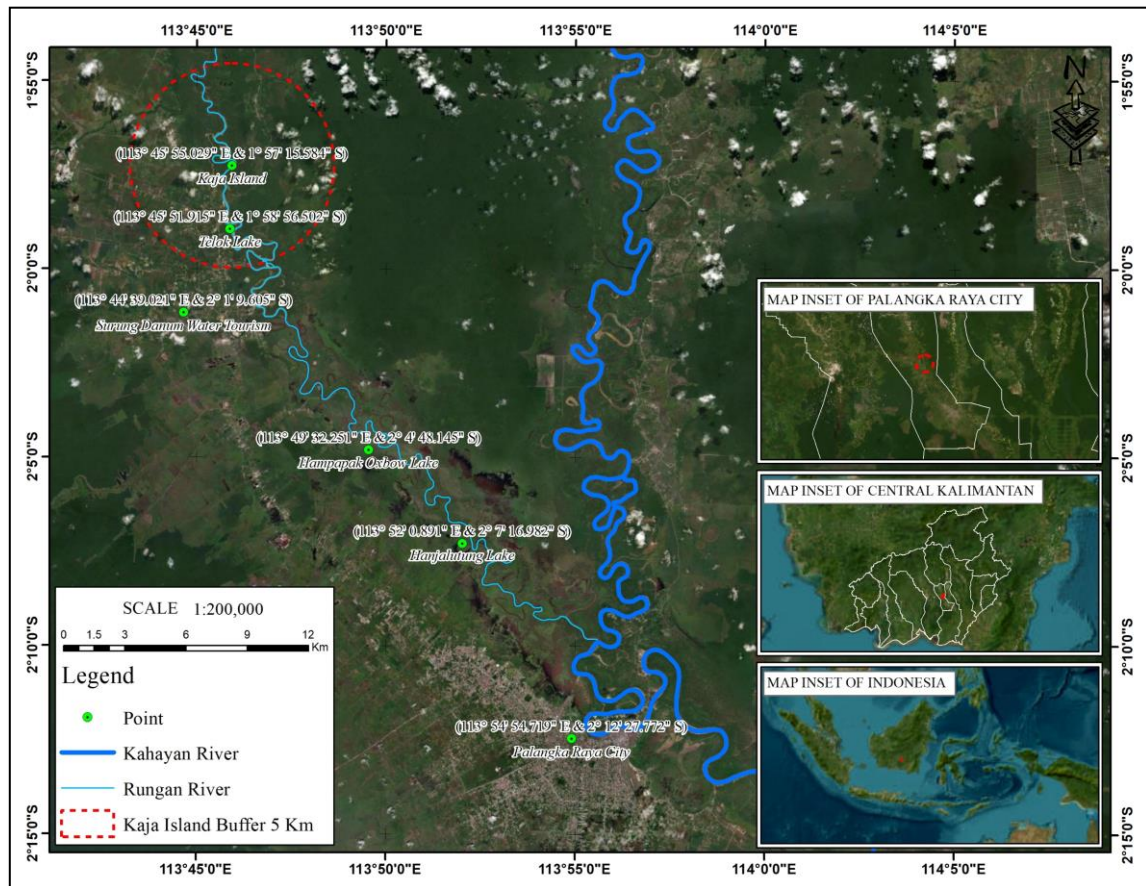


Figure 1. Map of the research location

2.2 Data analysis

2.2.1 Data category

The data were categorized based on their source (Rahmadi, 2011).

1) Primary Data: These are data obtained directly from the original source at the research location. In this study, primary data includes information on the condition of the Rungan Sub Basin ecosystem, the socio-economic data of the community, and the challenges faced by both the community and the government in managing the area. Socio-economic data were collected using interviews and Focus Group Discussions (FGDs). Interviews

were conducted using open- ended questions with 20 local community members, 10 Government Institution employees, 4 NGOs representatives and 2 Private sector representatives. In addition, two FGDs was conducted with local communities and other stakeholders.

2) Secondary Data: these are is sourced from non-primary references. In this study, secondary data include literature, Landsat images of land cover, population data of protected species, and other supporting data accessed online.

The analysis of ecosystem conditions aims to determine the area's status, potential, and threats,

serving as a key basis for preparing the Ruang Sub-Watershed management model. Understanding the significant value of an area is essential for minimizing potential negative impacts. At this stage, the required data primarily consists of secondary sources, including RTRW base maps, RTRW thematic maps, land capability unit maps, and large scale spatial data. The socio-economic descriptive analysis of the study area seeks to compile and elaborate on various data, incorporating both secondary information from local governments and primary data from surveys, to identify potential opportunities and challenges across different sectors.

2.2.2 Bio-physical analysis

Bio-physical analysis was carried out through a spatial approach and field surveys using the following steps.

a) Vegetation density analysis

Vegetation density analysis was conducted by examining land cover/land use and vegetation density using remote sensing imagery and land cover maps. The analysis of forest vegetation density classes utilized Normalized Difference Vegetation Index (NDVI) data from Landsat 8 OLI path/row 118061, dated July 26, 2024.

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

Where; NIR is the near-infrared reflectance and Red is the visible red light reflectance. This index helps to assess vegetation health by leveraging the fact that healthy vegetation absorbs a significant amount of red light and reflects a large amount of near-infrared light (Bannari et al., 1995; Kaufmann et al., 2003).

b) Physical land analysis

Physical land analysis in this study involved mapping peat depth classes and peat hydrological units using spatial data. This process employed a deductive approach to categorize the combined spatial data into distinct groups. The categories included peatland types, based on a combination of 20-cm contour-based peat elevation and peat depth data obtained from the Peat Ecosystem Function, as well as land cover categories that encompass various land cover types, permit areas, forest zones, and sub-peatland hydrological units.

c) Overlay and criteria combination

The overlay analysis approach was used to combine various spatial criteria to obtain appropriate zoning patterns. Commonly used tools included Intersect, Union, and Raster Calculator (for raster data).

The analysis process for vector data included:

1. Performing an Intersect between the 1-km buffer, HCV (High Conservation Value/NKT) layers, and land cover.
2. Adding the peat depth layer through the Intersect method or by converting the depth raster into polygons beforehand.

The classification system was conducted by assigning weighted values to each class within every criterion based on its importance for conservation or area management. The scoring table used was as follows Table 1.

Table 1. Criteria combination

Criteria	Class	Score
HCV (NKT)	HCV 1	3
	HCV 2	2
	Non-HCV	1
Peat	Deep (>3 m)	3
	Medium (2-3 m)	2
	Shallow (<2 m)	1
Land cover	Primary forest	3
	Shrub/Farmland	2
	Open land/Settlement	1

After assigning values, the scores of each criterion were summed for every spatial unit resulting from the overlay. This total score was then used to classify the zoning. Based on the calculated total scores, the zoning classification was determined as follows Table 2.

Table 2. Zoning score

Total score	Zoning
7-9	Core conservation zone
5-6	Buffer zone
3-4	General utilization zone

This classification served as the basis for decision-making in managing areas according to their environmental function and sensitivity based on data as follows Table 3.

Table 3. Summary of source of data

Data	Source
Social economic	Interview, observation, Central Bureau of statistic
Land cover	Digital land cover data interpreted from LDCM (The Landsat Data Continuity Mission)/Landsat 8 OLI imagery. Directorate of Forest Resource Inventory and Monitoring, Directorate General of Forestry Planning and Environmental Management
Peat soil depth	Provincial Spatial Plan (RPPEG) Map of Central Kalimantan Province
High conservation value biodiversity	High Conservation Value Biodiversity Map of Central Kalimantan Province
Forest area	Digital data of Forest Areas and Marine Conservation Areas of Indonesia as of December 2023, Directorate of Forest Area Establishment and Utilization, Directorate General of Forestry Planning and Environmental Management

3. RESULTS AND DISCUSSION

3.1 Landscape ecology

GIS analysis of vegetation density, peat soil depth, and land cover shows that the Rungan Sub-Watershed area spans 337,148 hectares, managed under various permits and designations. [Figure 2](#) illustrates that the predominant use of this area is oil palm plantations operated by private companies. Other management permits in the region include the Forest Cultivation Business License and Industrial Plantation Forest, covering areas of 64,835 hectares and 25,201 hectares, respectively. Additionally, permits granted to mining companies encompass approximately 25,928 hectares. The state forest area that remains free from company licensing totals 105,879 hectares.

The results of the land cover analysis indicate that deforestation has occurred to accommodate oil palm plantations and industrial timber plantations. Deforestation in river basins can affect the hydrological balance of rivers and trigger flooding ([Narendra et al., 2021](#); [Ramadhan et al., 2023](#)). Therefore, management of the Rungan Watershed should prioritize on conserving the remaining forest cover and rehabilitating degraded areas. Land rehabilitation models in watersheds should consider land function. Land rehabilitation models in conservation areas will apply different models and techniques compared to those in production forest areas ([Ruslan et al., 2018](#)).

There are 12 types of land use in the Rungan Sub-Watershed: rivers, non-residential buildings, residential buildings, lowland forests, peat swamp forests, plantation forests, gardens with mixed crops, natural open land, cultivated open land, oil palm plantations, inland swamps, and shrubs, as shown in [Figure 4](#). An analysis of the natural forest cover types—specifically lowland forests and peat swamp forests—reveals that the natural cover in this region is significantly influenced by river flows and their

hydrological cycles. The river area spans 940 hectares, while the inland swamp covers 188 hectares. [Figure 3](#) illustrates the distribution of peat depth, which is essential information for developing a zoning strategy.

Natural conditions and the factors affecting them are crucial considerations for area management strategies. Based on its function, the Rungan Sub-Watershed is divided into production forests, conversion production forests, other use areas, and sea waters. The largest proportion consists of production forests, comprising more than 50%, while conversion production forests and other use areas have nearly balanced proportions of 21.62% and 27.37%, respectively. The functions of the conversion and other areas suggest the potential for future changes in land use. This insight can inform the development of management strategies aimed at anticipating the loss of carrying capacity due to the conversion of forest land use.

3.2 Demography and livelihood

Based on secondary data from the Statistics Agency and results from field observations, the Rungan Sub-Watershed area encompasses more than 50 villages and sub-districts across Gunung Mas Regency and Palangka Raya City. The demographic characteristics of the community generally reflect those of rural areas, with low population density, a predominantly productive age group, and relatively low levels of education. The total population is approximately 45,000, with an average population density of less than 30 inhabitants per square kilometer.

The majority of the community consists of indigenous Dayak people, particularly Dayak Ngaju, along with a smaller number of immigrants from the Javanese, Banjar, and Bugis ethnic groups. Social and cultural ties remain strong, especially in the management of natural resources.

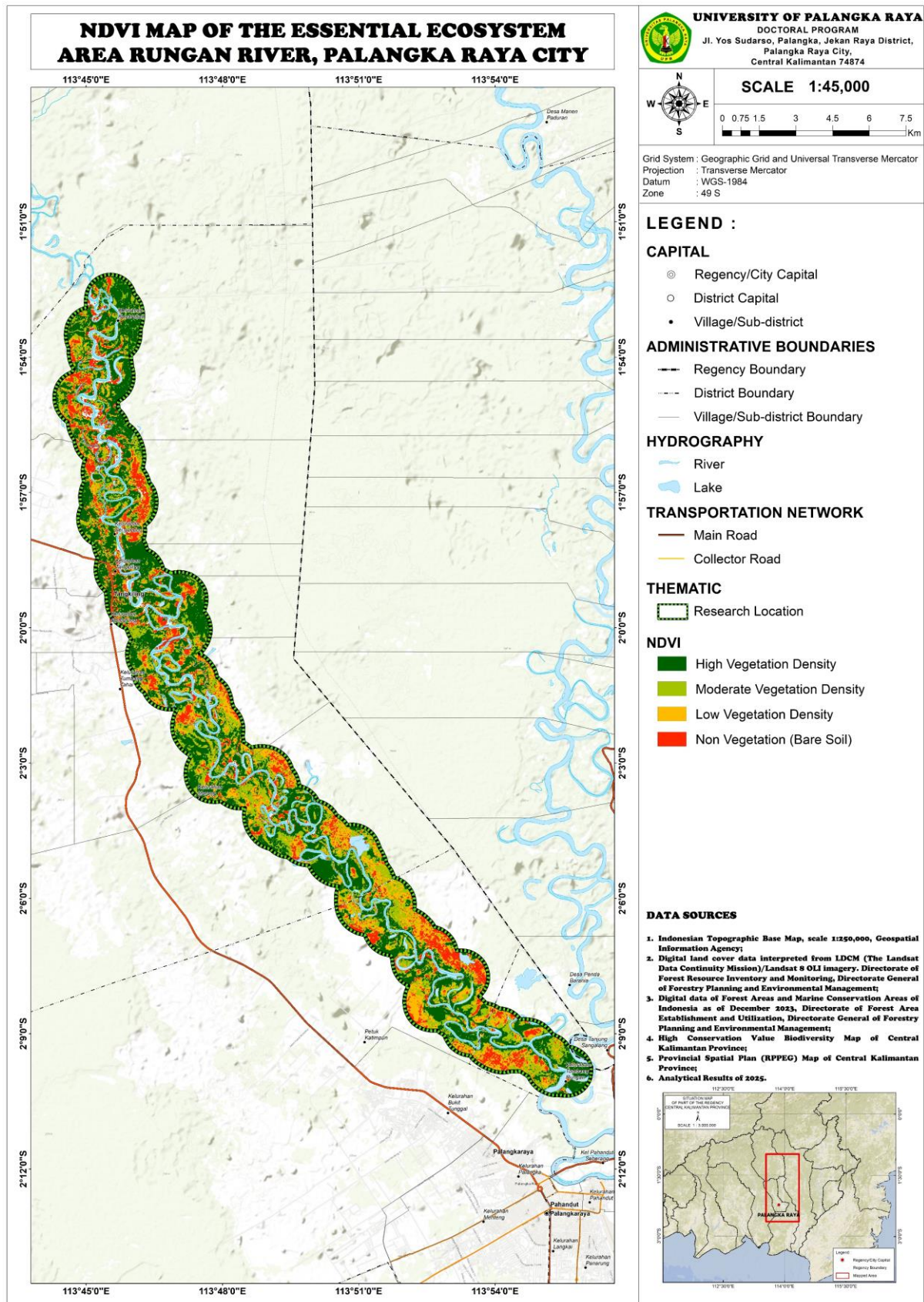
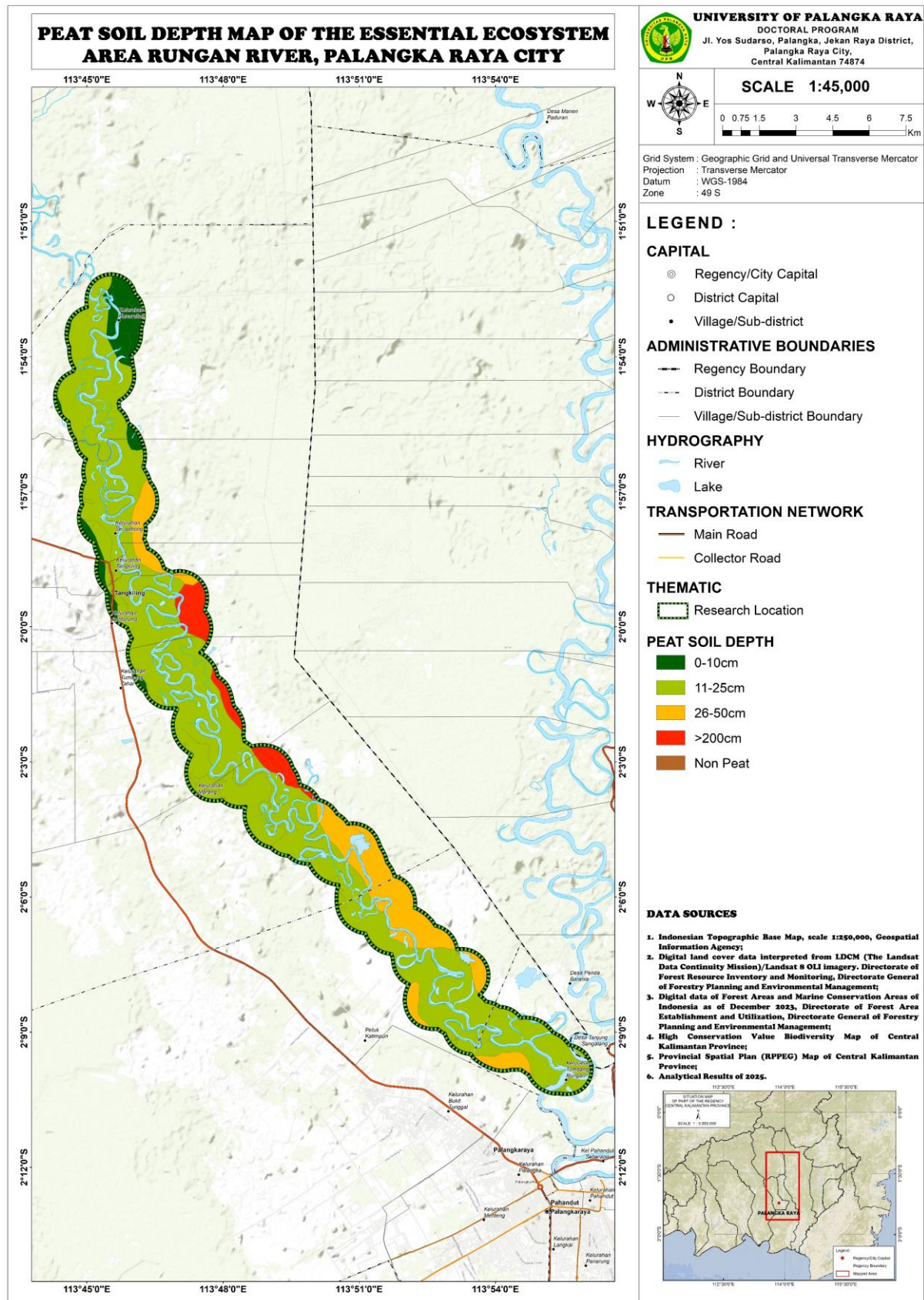


Figure 2. Map of vegetation density (NDVI Landsat 8) of Rungan Watershed



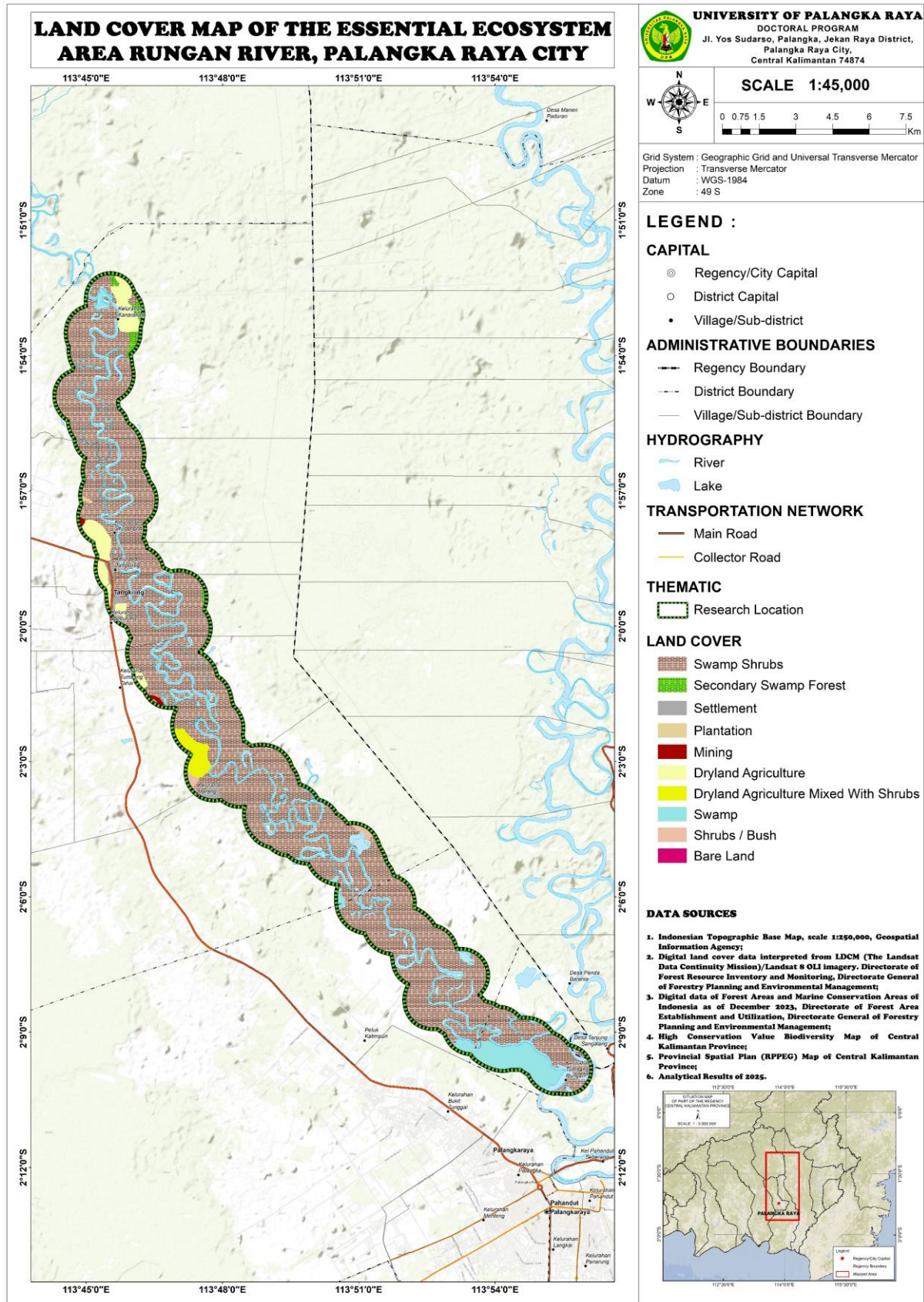


Figure 4. Map of land cover and land use of Rungan Watershed

The livelihoods of the people in the Rungan Sub-Watershed area heavily rely on natural resources

from rivers, forests, agricultural land, and gardens. Most community members engage in farming,

gardening, foraging for forest products, and fishing. Traditional methods of farming and gardening remain prevalent. Most of the community-owned plantations are in the form of agroforestry. These community agroforestry gardens provide a variety of products for subsistence and contribute to family income.

The results of secondary data analysis, community interviews and the expert opinions indicate several key socio-economic problems of the community, as follows:

- The community has a significant dependence on natural resources, including fisheries, plantations, and forest products. They lack access to modern technology to help them cope with extreme natural conditions, such as prolonged dry seasons, floods, and other hydrometeorological disasters. This vulnerability exposes them to damage from natural resource depletion and the impacts of climate change. A decline in the quality of these natural resources will profoundly affect their lives.
- The capacity of the community is still relatively low and has resulted in limited diversification of livelihoods. Furthermore, access to skill development opportunities is also limited, so most people do not have the skills to process natural or agricultural products into value-added products.
- The relatively low income of the community is one of the reasons for the limited processing of crops. In general, they still sell raw products.
- Another obstacle faced by the community is the limited marketing reach of the products they produce. Marketing is still local and conducted through collectors who come to the village. Limited access to financial institutions such as cooperatives and banks means that they lack sufficient capital to develop or intensify their livelihoods.
- There is a lack of integration between development and conservation programs. These two are still perceived as contradictory, with conservation efforts are often regarded as the limiting factor in people's livelihoods. However, if you look at the characteristics of people who have a depend on natural resources, conservation efforts can provide long-term security for livelihoods, whereas environmental degradation has negative impacts on people's livelihoods and well-being. Thus, there is a strong rationale for integrating natural resource conservation efforts with community welfare improvement. The development of a green economy that prioritizes the

principle of sustainability is one of the alternative solutions that can be offered.

The Rungan Sub-Watershed not only holds ecological richness, but also has high historical and cultural value. This area is part of the traditional residential area of the Dayak people, especially the Dayak Ngaju sub-tribe, who have lived and managed natural resources traditionally for hundreds of years. The traces of local civilization are imprinted in various aspects of life, ranging from belief systems, customs, land use, to the wisdom of ecosystem management.

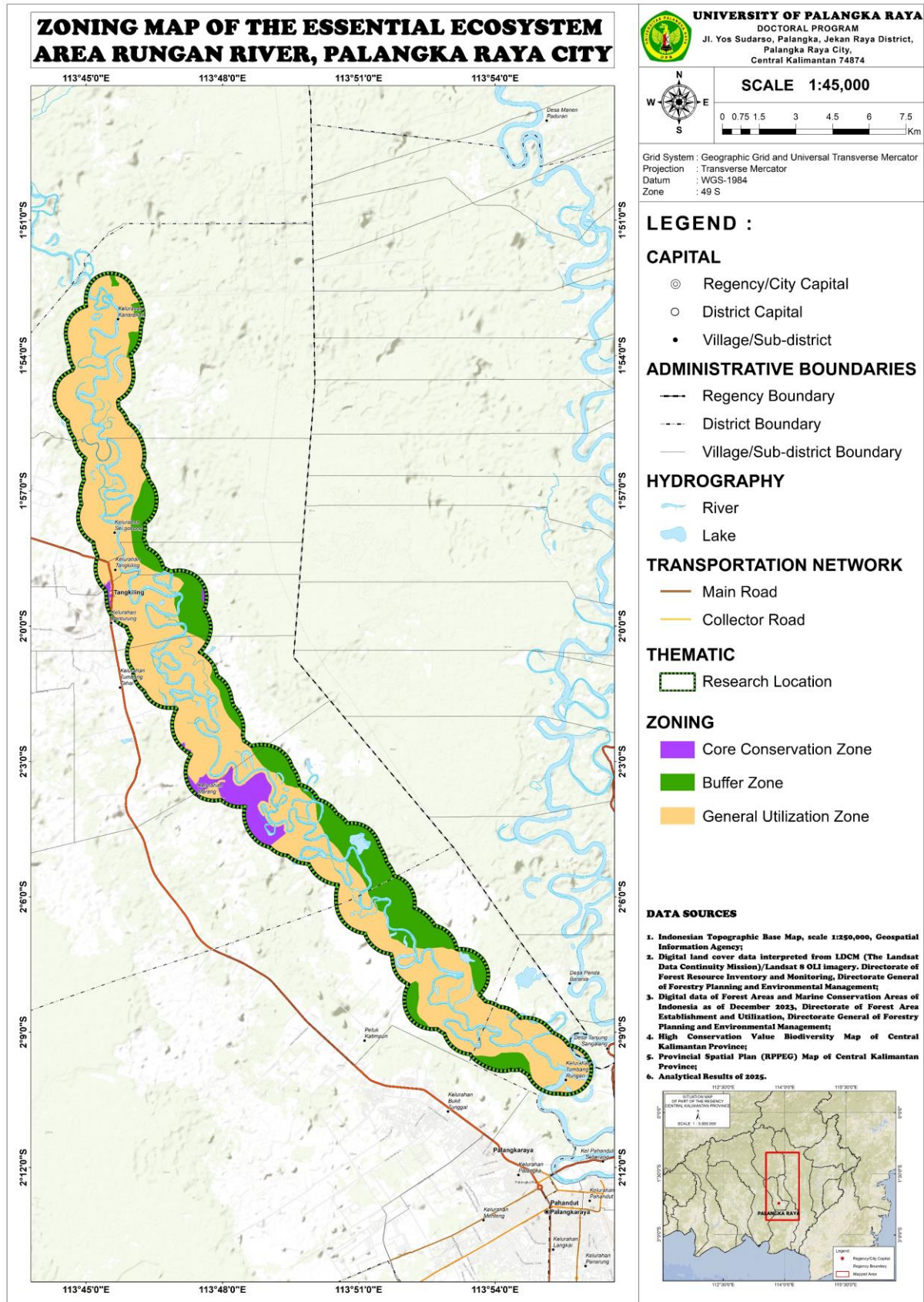
The utilization of forest resources by communities living around forests is one of the main focuses of forest empowerment programs. Forest and river environmental services are considered to have significant potential to contribute to improving community welfare (Wunder, 2001). However, this idea faces several limitations, such as limited access and rights over forest management, limited community capacity, and limited access to markets (Dewi et al., 2005).

3.3 Rungan Sub-Watershed management model and program

Based on biophysical analysis of the area, as well as socio-economic and cultural factors in the Sub-DAs Rungan region, this study formulates a management model.

The zoning arrangement model is part of spatial planning as stated in Indonesian Law No. 26/2007. Spatial planning is an activity that aims to regulate and supervise the use of space so that aligns with the Spatial Plan. These activities are carried out through zoning regulations, regulatory enforcement, incentives, permits and zoning control regulations (Lira, 2025).

The management zoning arrangement in the Rungan Sub-Watershed as shown in Figure 5, has a strategic role in addressing various problems while ensuring that diverse interests can be accommodated. Management zoning arrangements allow watershed ecological conservation and rehabilitation efforts to go hand in hand with community welfare improvement. The purpose of zoning is to establish the zoning of the Rungan River Essential Ecosystem Area in Palangka Raya City as the basis for spatial and thematic planning and management of the area. This zoning is intended to support efforts to conserve biodiversity, restore peat ecosystems, and manage natural resources sustainably. Zoning is carried out by considering the primary objectives of conservation, limited utilization, and risk-based management.



3.3.1. Core conservation zone

This area is designated as a core conservation zone due to its deep peat layers (greater than 3 meters), primary forest cover, and high biodiversity. These characteristics classify the zone as a high conservation priority. Land clearing and cultivation activities are prohibited in this zone to prevent damage to the ecological balance and the loss of biodiversity. Peatlands exceeding 3 meters in depth store significant carbon reserves, and converting them to agricultural land would release greenhouse gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere.

Several types of programs can be implemented in core conservation zones, including efforts to protect and secure the area, inventory and monitor its status and biodiversity, conduct research and scientific development, and raise public awareness for its protection. Protection efforts can involve forming area monitoring units in collaboration with the community, thereby fostering active participation and awareness simultaneously. Additionally, it is important to install warning signs that prohibit logging, hunting, and land burning.

3.3.2. Buffer zone

The buffer zone serves as a protective area surrounding the core conservation zone, shielding it from potentially damaging human activities. This zone has a dual purpose: to preserve the environment and to support community welfare (He and Jiao, 2023). While economic activities are allowed within this zone, priority is given to those that are environmentally friendly and cause minimal impact.

The Rungan Sub-Watershed, particularly around Kaja Island and Sei Gohong, has significant potential for development into an ecotourism and educational hub. Field observations indicate that this area could serve as a center for orangutan reintroduction, fishing tourism, and river tourism. However, the ecotourism potential has not yet been managed optimally and has not contributed significantly to community income. Interviews with local residents reveal that community participation in ecotourism development is currently limited to providing boat rental services, which generate additional income ranging from Rp. 250,000 to Rp. 500,000.

Ecotourism can be leveraged as a strategic tool for area management to support and enhance various programs. It can serve as the “face” of diverse activities, increasing their marketability. By

promoting ecotourism, land rehabilitation efforts, community fishing activities, and enterprises based on medicinal plants and local cuisine can be made more attractive and economically valuable. Ecotourism acts as a link between environmental potential, society, and nature, fostering greater awareness and appreciation for the environment, biodiversity, and cultural heritage among the broader public.

Educational tourism, in particular, is a form of tourism that provides information and knowledge to visitors. Educational tours will make conservation efforts such as watershed rehabilitation, tree planting, fish conservation and orangutan conservation more engaging and informative. This is a new breakthrough for the development of tourism in this region. Educational tourism also serves as a mechanism to broaden community benefits, while simultaneously increasing public awareness of the importance of environmental and cultural conservation.

3.3.3. General utilization zone

This zone typically features land cover consisting of gardens, agricultural fields, and secondary forests. It hosts various community based economic activities, including gardening, farming, fishing, and gold mining. One potential development program for this area is the rehabilitation of degraded land through agroforestry systems. The primary focus of this rehabilitation is the land adjacent to the river, aimed at preventing erosion and protecting the Rungan sub-watershed ecosystem.

Rehabilitation efforts can involve planting endemic species such as Balawan (*Tristanopsis stellata* Ridl.), Resak (*Vatica rassak*), and Kempas (*Koompassia malaccensis*) (Setiarno and Wittu, 2018), alongside economically valuable plants species such as rubber (*Hevea brasiliensis*), petai (*Parkia speciosa*), and durian (*Durio zibethinus*).

Another program aims to encourage the development of sustainable livelihoods (Natarajan et al., 2022; He and Jiao, 2023) including the use of non-timber forest products, sustainable fisheries, and ecotourism. Developing alternative livelihoods is essential for gradually shifting communities away from environmentally harmful practices, such as illegal gold mining in rivers and illegal logging.

4. CONCLUSION

This study concludes that the sub-watershed management must align with the bio-physical and ecological conditions of the area to address existing challenges and enhance community welfare. This can

be achieved by implementing zoning- based management system, in which the Rungan Sub-Watershed is divided into three zones: the core conservation zone, the buffer zone, and the general utilization zone. This zoning approach protects areas of high ecological value while allowing development to proceed, and encourages coordination and collaboration among stakeholders.

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AUTHOR CONTRIBUTIONS

Conceptualization, Writing-Original Draft Preparation; Writing-Review and Editing Endy, Randen Mas Sukarna; Writing, Formal Analysis, Endy, Herwin Sutrisno; Investigation, Methodology, Software, Resources, Validation, I Nyoman Sudana, Raden Mas Sukarna.

DECLARATION OF CONFLICT OF INTEREST

We declare that the manuscript titled “Management Model of Rungan Watershed Based on Landscape Ecology at Central Kalimantan” is an original scientific work that has not been published or is under review elsewhere. We confirm that all data, analyses, and interpretations are based on valid research methods and adhere to scientific standards. Proper credit has been given to all quotations, references, and contributions through appropriate citations. This manuscript contains no instances of plagiarism. We are prepared to accept consequences for any future publication ethics violations. All authors have made significant contributions to the research design, data analysis, and writing of the article. No authors are listed without substantial contributions.

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Influence of Environmental Factors and Heat Island Intensity on Outdoor Thermal Comfort Among Residents in Section 7, Shah Alam, Selangor, Malaysia

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ABSTRACT

The aim of this study was to investigate the influence of meteorological factors and urban heat island intensity (UHII) on outdoor thermal stress among residents in Section 7, Shah Alam, Selangor. Meteorological data, including temperature, relative humidity, and wind speed, were collected for Shah Alam from April to September 2024. The UHII was determined by subtracting the surrounding rural temperature from the urban temperature. The physiological equivalent temperature (PET) was calculated using RayMan software, and statistical analyses were conducted using the Statistical Package for the Social Sciences version 28. The UHII in Shah Alam ranged from 0°C to 3.7°C, with a mean of $0.743 \pm 0.687^\circ\text{C}$. The PET analysis indicated that 57.9% of the respondents reported warm perception of their environment (moderate heat stress), with PET values among respondents ranging from 25.90 to 32.00 and a mean of 29.121 ± 1.235 . A strong positive correlation was observed between temperature and PET ($r=0.835$, $p<0.001$), as well as a moderate positive correlation between UHII and PET ($r=0.404$, $p<0.001$), while a negative relationship was found between relative humidity and PET ($r=-0.579$, $p<0.001$). Temperature ($B=1.160$, $p<0.001$) and wind speed ($B=-0.911$, $p<0.001$) were significant predictors of PET among residents in Shah Alam. In conclusion, temperature and wind speed significantly influence outdoor thermal comfort in Section 7, Shah Alam. Local authorities should implement mitigation measures such as integrated urban planning, expanded green spaces and infrastructure, and sustainable land use, which can be effective solutions to reduce UHII and air temperature while enhancing wind flow and outdoor thermal comfort in urban areas.

HIGHLIGHTS

- The study found that Shah Alam exhibited a UHII between 0°C and 3.7°C.
- 57.9% of the respondents in Shah Alam experienced moderate heat stress.
- There were significant relationships among temperature, relative humidity, and UHII with PET ($p<0.001$).
- An increase in temperature in Shah Alam would lead to an increase in the PET value ($B=1.160$, $p<0.001$).
- An increase in wind speed in Shah Alam would lead to a decrease in the PET value ($B=-0.911$, $p<0.001$).

1. INTRODUCTION

Rapid urbanization has significantly altered local microclimates, particularly in urban areas where air temperature has risen dramatically. This increase has raised concerns about urban heat islands (UHIs) and the thermal performance of open spaces within

city areas (Ishak et al., 2023). Thermal comfort and air temperature levels are influenced by factors such as building mass, canopy height, and spatial arrangement, which are closely related to the built-up areas in urban settings (Eslamirad et al., 2023).

The intensification of UHI effects poses

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additional challenges to outdoor thermal comfort, primarily due to rising air temperature and heatwaves in urban areas (Eslamirad et al., 2023; Ren et al., 2023). Compared to suburban and rural regions, urban areas experience significantly warmer conditions, which can compromise the health and safety of city dwellers due to poor thermal comfort (Kalogeropoulos et al., 2022). This decline in comfort negatively affects the quality of life in urban space, residents' satisfaction, and overall urban thermal performance (Aghamolaei et al., 2023; Kalogeropoulos et al., 2022). Prolonged exposure to a poor thermal comfort environment may increase the risk of heat-related illnesses, such as heat exhaustion and heat stroke, among the urban population (Abdel-Ghany et al., 2013; Kurazumi et al., 2019). Therefore, understanding the relationship between environmental factors and UHI effects on thermal comfort is essential. Such understanding can enable authorities to develop effective mitigation strategies to address outdoor thermal stress, ultimately protecting residents from adverse health outcomes.

In addition, outdoor thermal comfort can be evaluated using the physiological equivalent temperature (PET), a thermal index that estimates the thermal component within a given environment (Deb and Alur, 2010). Physiological equivalent temperature reflects the relationship between the atmospheric environment and human thermal perception by integrating various meteorological factors, such as air temperature, relative humidity, and wind speed (Matzarakis and Mayer, 1996). Among various thermal indices, PET is the most widely used for assessing outdoor thermal comfort and has proven effective in evaluating thermal exposure in urban settings (Gomaa et al., 2024; Ren et al., 2023).

This study aims to investigate the influence of meteorological factors and urban heat island intensity (UHII) on outdoor thermal stress, as measured by the PET among residents in Section 7, Shah Alam, Selangor. The research focuses on analyzing the relationship among UHII, key meteorological factors, and PET values. The PET values can be translated into thermal sensation and physiological stress levels, representing outdoor thermal comfort among residents in Shah Alam, Selangor. Additionally, this study seeks to determine the predictive factors for PET, which may support the development of targeted mitigation measures to address the thermal impacts of urbanization in Shah Alam.

2. METHODOLOGY

2.1 Study area

This study was conducted in Section 7, which is located within Shah Alam, the state capital of Selangor, Malaysia, specifically in the commercial and recreational areas of Shah Alam, where the population is frequently exposed to outdoor environments. Shah Alam is an urban area under the jurisdiction of Shah Alam City Council. Section 7, Shah Alam, is a rapidly urbanizing area in Selangor, Malaysia, featuring dense development, educational hubs like Universiti Teknologi MARA (UiTM), and a tropical rainforest climate (Shah Alam City Council, 2025). Its mix of infrastructure, green spaces, and strategic locations makes it a key site for studying UHIs, land use changes, and sustainable city planning (Department of Statistics Malaysia, 2023). Figure 1 shows the location of the study in Shah Alam.

2.2 Data collection

This study involved the collection of six months of meteorological data (April-September 2024), including temperature, relative humidity, and wind speed for Shah Alam, Selangor. Since Shah Alam does not have its own meteorological station, data from the nearest available station, Subang Jaya Meteorological Station, located approximately 7 km away, was used to represent the meteorological conditions in Shah Alam. A limitation of using meteorological data from Subang Jaya is that the data may not entirely represent local microclimates, such as wind and rainfall in Shah Alam. The use of meteorological data from Subang Jaya Meteorological Station was considered due to several factors: Both areas are classified as urban areas, the distance between the two locations is less than 10 km, and both areas are exposed to Malaysia's similar tropical climate, which is unlikely to vary greatly between them. Additionally, temperature data from a reference rural station, Pusat Pertanian Kalimpan in Hulu Selangor, were obtained to calculate the UHII for Shah Alam. The UHII was determined by subtracting the surrounding rural/suburban temperature from the urban temperature, as shown in Equation 1 (Ramakreshnan et al., 2019).

$$\text{UHII} = T_{\text{urban}} - T_{\text{rural}} \quad (1)$$

Where; UHII=Urban heat island intensity;
 T_{urban} =Average air temperature in the urban area;
 T_{rural} =Average air temperature in the nearby rural area

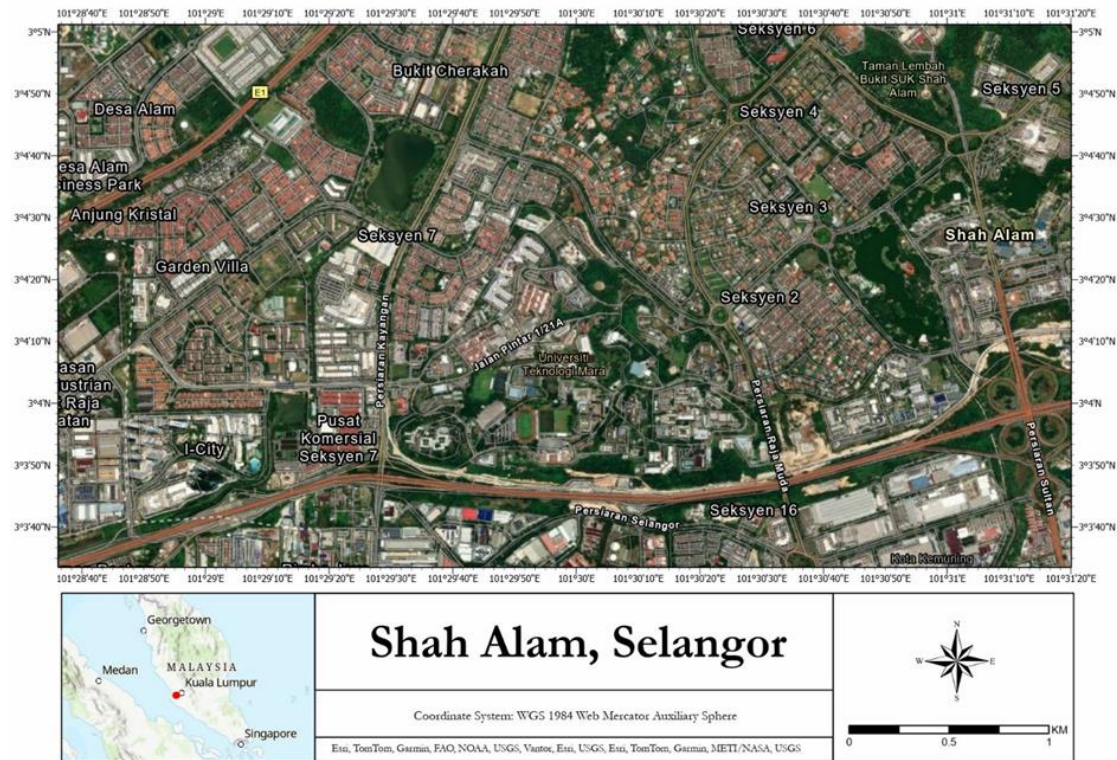


Figure 1. Study location in Shah Alam (Source: WGS 1984 Web Mercator Auxiliary Sphere)

Physiological equivalent temperature was calculated using RayMan software, which simulates the human thermal environment based on temperature, relative humidity, and wind speed from meteorological data and residents' information (height, weight, age, gender, clothing factors, and activity) collected using questionnaires distributed to 183 residents in Section 7, Shah Alam. The inclusion criteria for respondents were residents aged more than 20 years old to 50 years old; permanent residents of Section 7, Shah Alam, for at least one year; Malaysian citizens; and individuals who frequently engage in outdoor activities in the area. The inclusion criteria of the respondents allow the study to obtain PET values that represent the human thermal environment among residents in Shah Alam. However, individuals under 20 and above 50 years were removed due to potential differences in thermal homeostasis responses. Therefore, the findings of this study may not represent those under 20 and above 50 years old and may not be generalizable to the entire population of Shah Alam. After obtaining the meteorological data for Shah Alam, including temperature from the reference meteorological station and PET values, all data were sorted and cleaned using Microsoft Excel 2019 before

being imported into the Statistical Package for the Social Sciences (SPSS) version 28.

2.3 Data analysis

Using SPSS version 28, descriptive analyses were conducted on temperature (Shah Alam and the reference station), relative humidity, wind speed, PET, and UHII. To obtain PET data for each respondent, meteorological data (temperature, relative humidity, and wind speed) and residents' height, weight, age, gender, clothing factors, and activity information were entered into the RayMan software before the PET values could be generated. All data were tabulated as means, standard deviations, minimums, and maximums, while thermal perception was presented in terms of frequency and percentage. This was done to provide an overview of the obtained data prior to further statistical analyses. Thermal sensation and physiological stress levels were determined based on PET values to describe the outdoor thermal comfort experienced by residents in Shah Alam during the study period. Table 1 shows the categorization of thermal sensation and grade of physiological stress levels based on PET values.

Table 1. Categorization of thermal sensation and grade of physiological stress levels based on PET values

PET value (°C)	Thermal sensation	Grade of physiological stress
<4	Very cold	Extreme cold stress
4-8	Cold	Strong cold stress
8-13	Cool	Moderate cold stress
13-18	Slightly cool	Slight cold stress
18-23	Comfortable	No thermal stress
23-29	Slightly warm	Slight heat stress
29-35	Warm	Moderate heat stress
35-41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

Source: [Matzarakis and Mayer \(1996\)](#); [Stojićević et al. \(2016\)](#)

Additionally, SPSS version 28 was also used to examine the relationship between meteorological factors and UHII with PET. Pearson correlation analysis and stepwise linear regression were employed as part of the statistical analysis. Pearson correlation identifies the strength and direction of the linear relationship between meteorological factors and UHII with PET, while linear regression assesses the relationship between the tested variables, indicating how changes in meteorological factors and UHII affect PET among residents in Shah Alam, Selangor. This approach allows for the identification of significant predictors influencing PET values in urban areas. For the regression model, the stepwise method was used instead of the enter method because the former adds or removes variables based on their statistical significance, rather than forcefully adding all variables into a regression model. All collected data were processed and tested to meet the assumptions of Pearson correlation (e.g., normality of data, absence of outliers, and linear relationship between variables) and stepwise linear regression (e.g., linearity,

homoscedasticity, normality of residuals, and independence of errors) prior to the analysis. This ensures that the selected statistical analysis provides validity and reliability of the findings, preventing inaccurate interpretations and predictions of the data.

3. RESULTS

3.1 Meteorological factors in Shah Alam

A descriptive analysis of the meteorological factors in Shah Alam is presented in [Table 2](#). The minimum and maximum temperatures recorded in Shah Alam, Selangor were 25.9°C and 31.1°C, respectively, with the mean and standard deviation (SD) for the temperature of 28.784±1.038°C. These values were higher than those recorded at the control station, where the minimum and maximum temperatures were 24.0°C and 29.4°C, respectively, with a mean of 27.040±0.827°C. The relative humidity recorded a minimum value of 61.7% and a maximum value of 88.8%, with a mean of 76.435±5.956%. The wind speed in Shah Alam ranged from 0.60 m/s to 3.70 m/s, with a mean of 1.701±0.481 m/s.

Table 2. Descriptive analysis of meteorological factors

Meteorological parameters	N	Min	Max	Mean	SD
Temperature (°C)	183	25.90	31.10	28.784	1.038
Temperature (reference station) (°C)	183	24.00	29.40	27.040	0.827
Relative humidity (%)	183	61.70	88.80	76.435	5.956
Wind speed (m/s)	183	0.60	3.70	1.701	0.481

3.2 Urban heat island intensity in Shah Alam

Urban heat island intensity was derived from the temperature difference between Shah Alam and a reference station located in a rural area. [Figure 2](#) shows the temperature difference between these two locations. It was found that, during the period from 1st April until 30th September 2024 (183 days),

temperatures in Shah Alam were generally slightly higher than those at the reference station in the rural area, indicating the presence of a UHI effect in Shah Alam. These temperature differences correspond to the UHII, where the intensity in Shah Alam ranged between 0.0°C and 3.7°C, with a mean of 1.743±0.687°C ([Table 3](#)).

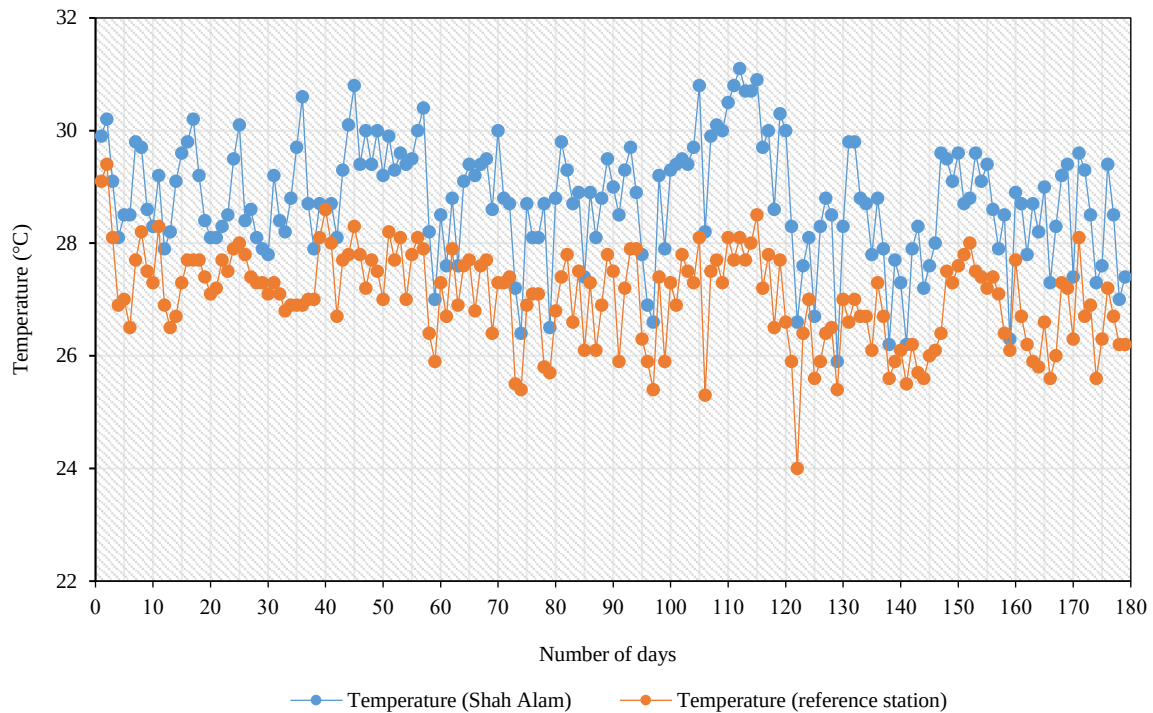


Figure 2. Temperature differences between Shah Alam and the reference station

3.3 Physiological equivalent temperature

Regarding the PET, the values among residents in Section 7, Shah Alam ranged from 25.9 to 32.0, with a mean of 29.121 ± 1.235 (Table 3).

The PET value can be translated into the thermal perception experienced by residents in Section 7, Shah Alam, allowing for the grading of the

physiological stress that they experience. This provides an indication of the outdoor thermal comfort experienced by the residents of Shah Alam. It was found that 42.1% of the residents felt slightly warm, which corresponds to slight heat stress, while 57.9% of the residents felt warm or experienced moderate heat stress (Table 4).

Table 3. Descriptive analysis of UHII and PET

	N	Minimum	Maximum	Mean	SD
UHII	183	0.00	3.70	1.743	0.687
PET	183	25.90	32.00	29.121	1.235

Table 4. Thermal perception and grade of physiological stress

Thermal perception	Frequency (n)	Percentage (%)	Grade of physiological stress
Slightly warm	77	42.1	Slight heat stress
Warm	106	57.9	Moderate heat stress

N=183

3.4 Correlation between meteorological factors and UHII with PET

This study found a trend of increasing PET values with increasing UHII and temperature, while PET values decreased with higher relative humidity. A slight increase in PET values was also observed with increasing wind speed. Figure 3 shows the trends of

PET values in relation to UHII, temperature, relative humidity, and wind speed.

The results for the Pearson correlation analysis between meteorological factors and UHII with PET are presented in Table 5. The results indicate that temperature ($r=0.835$, $p<0.001$) and UHII ($r=0.404$, $p<0.001$) have positive relationships with PET,

meaning that increases in temperature and UHII will increase PET values. On the other hand, relative humidity shows a negative relationship with PET ($r=-0.579$, $p<0.001$), indicating that increases in relative

humidity will reduce PET values. No relationship was found between wind speed and PET ($r=0.038$, $p=0.614$), suggesting that changes in wind speed do not affect the PET values experienced by residents.

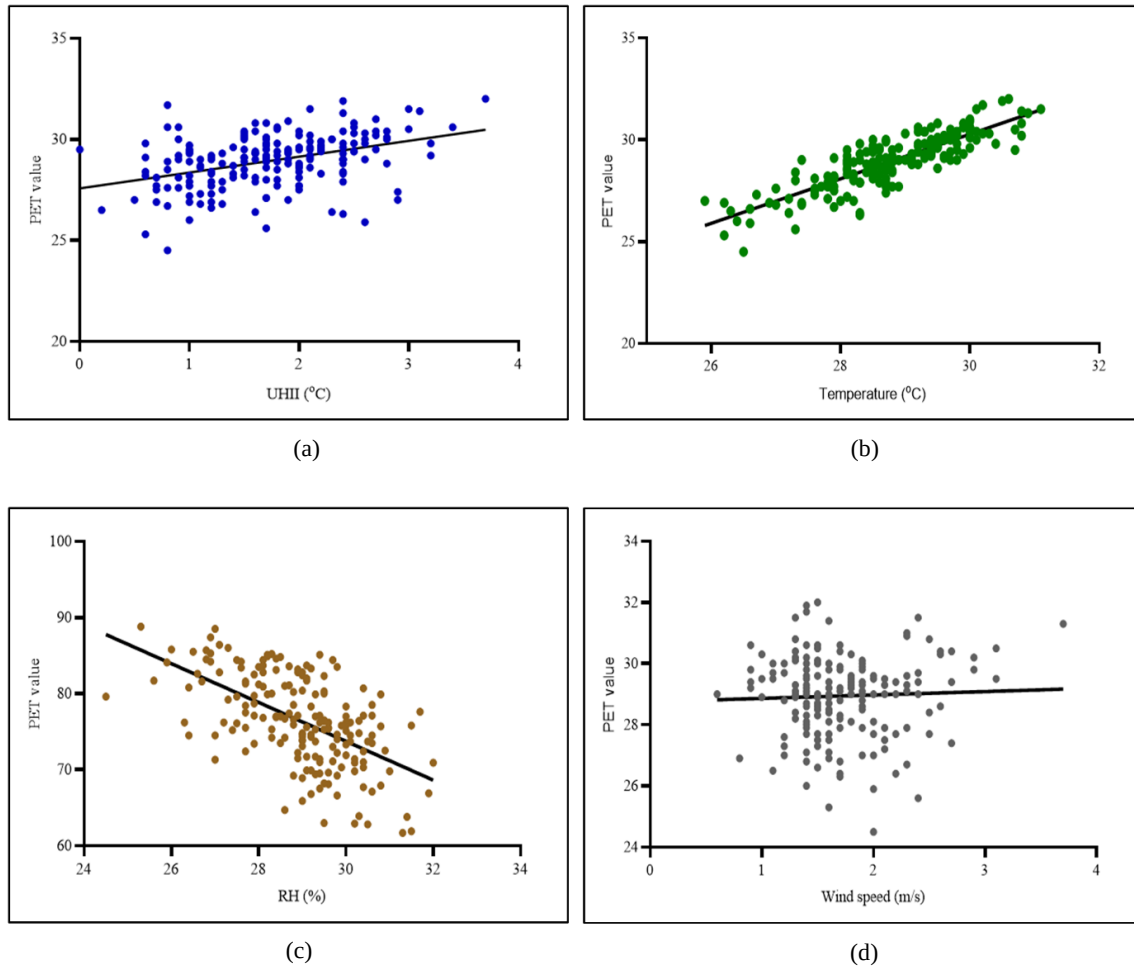


Figure 3. Trends of PET values with (a) UHII, (b) temperature, (c) relative humidity, and (d) wind speed

Table 5. Correlation between meteorological parameters and UHII with PET

Parameters	r	p
Temperature (°C)	0.835	<0.001
Relative humidity (%)	-0.579	<0.001
Wind speed (m/s)	0.038	0.614
UHII (°C)	0.404	<0.001

3.5 Predictors for PET

A stepwise regression analysis was performed to examine the relationship between meteorological factors and UHII with PET, as shown in Table 6. The stepwise regression finalized the model by including temperature and wind speed as predictors of PET

while removing relative humidity and UHII, as both factors did not significantly contribute to the model.

Based on Table 6, the correlation coefficient (R) was 0.901, indicating a good level of prediction of PET values using temperature and wind speed. In addition, the coefficient of determination (R^2) was 0.812, which means that the temperature and wind speed explain 81.2% of the variation in PET values. After adjustment ($\Delta R^2=0.810$), the independent variable explains 81% of the variation in PET values in this model. The F-ratio for the regression model was $F(2, 182)=378.375$, $p<0.001$, indicating that the independent variables significantly predict the dependent variable. These results demonstrate that the regression model provides a good fit of the data.

Table 6. Stepwise regression analysis of predictors for PET

	B	SE	β	t	p	F	R	R ²	ΔR^2	Sig.
Model 1										
Temperature	0.988	0.048	0.840	20.738	<0.001	430.069	0.840	0.705	0.703	<0.001
Model 2										
Temperature	1.160	0.042	0.986	27.803	<0.001	378.375	0.901	0.812	0.810	<0.001
Wind speed	-0.911	0.090	-0.359	-10.119	<0.001					

Model 2 shows that for every 1.160°C increase in temperature, the PET value increases ($B=1.160$, $p<0.001$). Conversely, for every 0.911 m/s increase in wind speed, the PET value experienced by residents in Section 7, Shah Alam, decreases ($B=0.911$, $p<0.001$). This highlights that as temperature rises, the PET value also increases, which can affect thermal perception (slightly warm, warm, hot, and very hot perception) and physiological stress (slight, moderate, strong, and extreme heat stress) among residents. Meanwhile, the increase in wind speed results in a decrease in the PET value ($B=-0.911$, $p<0.001$), emphasizing the cooling effect provided by the wind speed, which may improve thermal perception and reduce physiological stress among the residents.

4. DISCUSSION

Urbanization and the expansion of urban areas have long been associated with the reduction of green cover and the concurrent increase in air temperature due to the UHI effect (Bian et al., 2025). Urban development often involves replacing vegetation with thermally conductive and heat-retaining materials, which leads to higher ambient temperatures in the affected areas (Asnawi et al., 2024; Cheela et al., 2021). The UHI phenomenon reflects environmental responses to land use and land cover changes in developed areas, contributing to a gradual increase in UHII over time (Rendana et al., 2023).

In this study, Shah Alam exhibited clear UHI characteristics, with a maximum recorded UHII of 3.7°C. This value is significantly higher than the UHII of 0.7°C reported in Hulu Langat, Selangor, in 2021. The elevated UHII in Shah Alam may be attributed to a pronounced trend in land cover transformation, characterized by expanding built-up areas and declining vegetation, particularly in the Klang Valley region where Shah Alam is located (Azari et al., 2022). This finding highlights the effect of urbanization and land use and land cover changes on urban areas, contributing to rising air temperatures and increasing UHII.

Moreover, land use and land cover changes have been associated with outdoor thermal comfort, as built-up areas in urban environments may promote heat stress among urban residents compared to those living in suburban or rural areas (Yeo et al., 2021). As urban heating driven by UHI, global warming, and extreme climate events becomes more pronounced, concerns about outdoor thermal comfort and public health risks have intensified (Dzyuban et al., 2022). Meteorological factors such as air temperature, wind speed, and relative humidity, along with personal activities (both static and dynamic), significantly influence thermal perception in open spaces (Bian et al., 2025; Yeo et al., 2021). On the other hand, PET has been frequently used as an evaluation indicator for different comfort levels in several studies focusing on outdoor thermal comfort (Bian et al., 2025; Qi et al., 2025). Therefore, examining temperature, relative humidity, and wind speed together with UHII as potential factors influencing PET can enhance our understanding of the relationship between environmental factors and outdoor thermal comfort in urban settings.

A previous study conducted in Penang, Malaysia, highlighted the PET values found in transitional areas (a sky court, a balcony, and a rooftop garden), which may affect outdoor thermal comfort among occupants. The study reported PET values below 34°C, similar to this study, which found the highest PET at 32°C. However, the thermal comfort range of respondents was broader than the Western or Middle European scale (19-30°C) (Taib and Ali, 2016). A study conducted in Shah Alam Lake Garden, a public park, found that thermal perception based on the PET value of the study indicated that the respondents adapted to the warm perception in the area, which is similar to this study, as more than half of the respondents felt warm as thermal perception (Nasir et al., 2012). These findings suggest that outdoor thermal comfort for the population in Shah Alam can be expected at a warm level, owing to local

meteorological conditions and personal factors of the respondents living in the area.

The findings of the current study revealed a positive relationship between air temperature and UHII with PET, indicating that increases in temperature and UHII correspond to higher PET values in Shah Alam. Conversely, PET was observed to decrease with higher relative humidity levels. Interestingly, despite existing literature highlighting wind speed as a key determinant of thermal comfort, no significant correlation between wind speed and PET was found in this study. However, stepwise regression analysis identified both air temperature and wind speed as significant predictors of PET variations among residents in Shah Alam.

Previous research suggests that lowering relative humidity as temperature increases can improve thermal comfort, while insufficient wind speed can hinder heat dissipation from the human body (Dec et al., 2018). Lower relative humidity facilitates sweat evaporation, and increased wind speed enhances convective cooling, both of which contribute to improved thermal comfort (Dec et al., 2018). Moreover, fluctuations in air temperature have been closely linked to thermal discomfort, with higher temperatures and increased human metabolic heat generation inducing a stronger sensation of heat stress (Hou, 2018). The negative impact of rising temperatures on thermal sensation can be mitigated by increased airflow.

This study has several limitations. First, the use of meteorological data on temperature, relative humidity, and wind speed, rather than measurements of the local microclimate in Shah Alam, may not represent the actual exposure to the urban environment experienced by residents in the study areas, which can affect their thermal comfort levels. Second, although PET is a commonly used thermal index to assess thermal comfort, it was calculated using environmental data and information from residents. The study did not include measurements of heat stress or physiological changes, such as variations in body temperature, heart rate, or breathing rate, which could provide clearer evidence on the implication of the urban environment on thermal comfort among residents. Third, the study was performed in public areas where residents engaged in moderate outdoor activities, rather than in outdoor spaces where residents may perform moderate to vigorous outdoor activities, making them more susceptible to environmental factors that affect their comfort levels.

Due to these factors, the PET values and thermal perception obtained may not entirely represent the residents of Shah Alam, as the data used for PET calculations were sourced from a meteorological station instead of field measurements within the study area. Local microclimates may differ from one area to another in Shah Alam. The PET values can be used to determine residents' thermal comfort. However, due to the subjective nature of the information obtained through questionnaires, such as clothing factors and activities, the accuracy of thermal comfort levels may need to be supported by personal measurements to provide quantitative evidence of thermal comfort. This study also did not include respondents engaged in vigorous outdoor activities, which may adversely affect their outdoor thermal comfort; thus, the findings may only represent Shah Alam residents performing low to moderate outdoor activities. Future research should address these limitations by incorporating local microclimate measurements, physiological monitoring, and a broader range of activity settings. Consideration should also be given to outdoor thermal comfort during extreme weather events, such as heatwaves, with a focus on vulnerable target groups, including children, the elderly, and outdoor workers, who can be adversely affected by surrounding environments, such as exposure to high temperatures during their daily activities.

5. CONCLUSION

In conclusion, this study has examined the influence of meteorological factors, such as temperature, relative humidity, wind speed, and UHII, on outdoor thermal stress, as measured by the PET among residents in Section 7, Shah Alam, Selangor. Temperature and wind speed were found to be the strongest predictors of PET among these residents. However, the roles of UHII and relative humidity in shaping PET should not be overlooked, as both factors also demonstrate a notable impact on thermal comfort among residents in the urban environment. Moreover, UHII was observed to contribute to increased heat stress among residents. With ongoing rapid urbanization in Shah Alam and its surrounding areas, temperature and UHII in Shah Alam are projected to rise, which may further degrade outdoor thermal comfort in the near future. Consequently, this may adversely affect the outdoor thermal comfort experienced by local residents, potentially leading to heat stress and related illnesses that threaten the health

and well-being of residents engaged in outdoor activities in urban areas.

To address these challenges, proactive measures must be undertaken by local authorities and urban planners to mitigate the impact of urbanization on the local microclimate and UHI effects. Such measures include incorporating green infrastructure into urban design, transitioning to renewable energy sources, promoting public transportation, expanding green spaces, encouraging sustainable land use, and adopting circular economy practices to minimize greenhouse gas emissions. These efforts are crucial for supporting Shah Alam and other similar cities in achieving Sustainable Development Goal 11: sustainable cities and communities, which aims to make cities inclusive, safe, resilient, and sustainable.

AUTHOR CONTRIBUTIONS

Conceptualization, N Mohamed; Methodology, NFAM Zeini and NIHK Anwar; Investigation, NFAM Zeini and N.I.H.K. Anwar; Formal analysis-MAM Aminuddin; Visualization; Supervision, N Mohamed; Writing original draft, N Mohamed; Review and editing, N Mohamed.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Process Optimization of Glycerol-to-Triacetin Conversion in Clean Technology Applications: In Situ Water Removal for Enhanced Reaction Performance in Sustainable Biodiesel Byproduct Valorization

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ABSTRACT

Increasing biodiesel production generates excess glycerol, which has a declining economic value. Converting glycerol into triacetin, a value-added fuel additive, offers a promising solution. However, the reversible nature of the esterification reaction and the formation of water reduce selectivity. Therefore, this study was conducted to evaluate the effect of in situ water removal on reaction performance in terms of acetic acid conversion and the resulting triacetin product. Experiments were conducted in a batch reactor through three clearly defined stages. In Stage 1, the optimal glycerol-acetic acid molar ratio (1:3-1:5) was determined at 100°C and 700 rpm, using a 5% natural zeolite catalyst (based on acetic acid mass), and a reaction time of 4 h with in situ water removal. In Stage 2, residual water was removed by fractional distillation at 105°C until bubbling ceased. Stage 3 comprised the main reaction, where the distillate containing monoacetin, diacetin, triacetin, and glycerol was reacted with fresh acetic acid at the optimal ratio, while in situ water removal continued to enhance triacetin formation. Acetic acid conversion was analyzed by acid-base titration using 0.5 N NaOH, and triacetin was identified by GC-MS. This innovation showed excellent results, achieving 94.00% conversion of acetic acid with 85.58% selectivity for triacetin at 110°C and a 1:5 glycerol-to-acetic acid molar ratio. These results showed that in situ water removal intensified esterification by shifting the equilibrium, enhancing triacetin conversion and selectivity. This strategy advances glycerol valorization and supports the production of sustainable fuel additives within integrated biorefinery systems.

HIGHLIGHTS

- In situ water removal boosts triacetin synthesis efficiency and selectivity.
- Three-stage esterification enhances acetic acid conversion up to 94.00%.
- Optimal at 110°C and 1:5 molar ratio, achieving 85.58% triacetin selectivity.
- Kinetic study fits a second-order model with strong correlation ($R^2 \geq 0.94562$).

1. INTRODUCTION

Biodiesel production as a renewable energy source continues to increase and generates glycerol as a byproduct at approximately 10% of the total production capacity (Khan et al., 2025; Bansod et al., 2025). The accumulation of glycerol causes oversupply in the global market and reduces its economic value (Sriratchachawan et al., 2022), and it potentially becomes waste when the purification cost

is higher than its selling price. One strategy to increase its added value is to convert glycerol into triacetin as a biodiesel fuel additive to improve combustion performance and fuel viscosity stability (Singare et al., 2025; Guimarães et al., 2025). Triacetin is produced through an esterification reaction between glycerol and acetic acid, and the reaction rate can be accelerated by using porous solid catalysts (Figure 2)

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(Sandid et al., 2024). This reaction is reversible and produces water as a byproduct, which can shift the equilibrium toward the reactants and reduce triacetin selectivity (Figure 1). Therefore, water control during the reaction becomes a crucial aspect. For the reaction to proceed effectively, the reactants, namely acetic

acid and glycerol, must reach the active sites of the catalyst, because the reaction can only occur efficiently at those sites. The stages of glycerol esterification with acetic acid using a porous solid catalyst are illustrated in Figure 2.

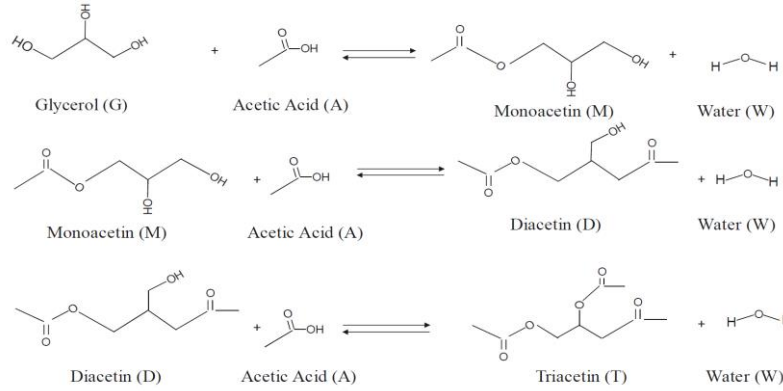


Figure 1. Esterification reaction steps of acetic acid and glycerol to produce triacetin

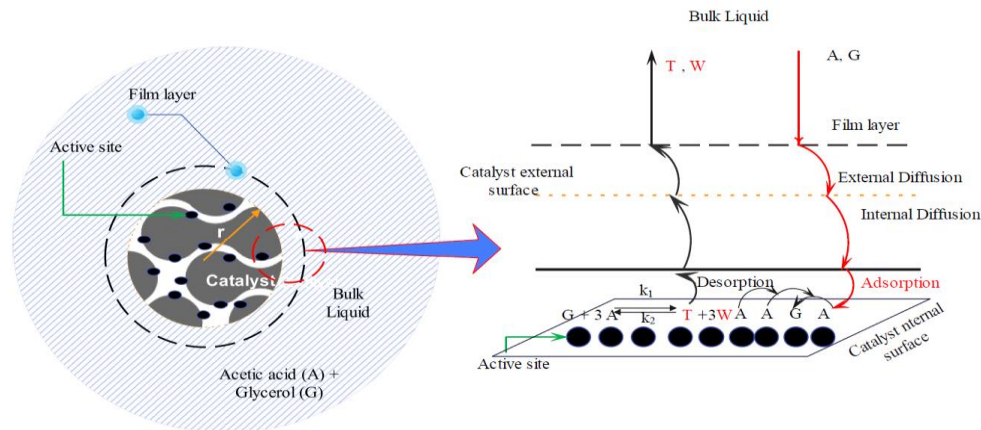


Figure 2. Illustration of the triacetin synthesis steps using a porous solid catalyst

Under steady-state conditions, the rates of external diffusion, internal diffusion, adsorption, desorption, and reaction are equal (Figure 2). Because this study adopted a steady state approach, the kinetic modelling was developed using an overall reaction rate approach, in which the adsorption rates of the reactants (glycerol and acetic acid), as well as the desorption rates of the products (triacetin and water), were not modeled as separate rate determining steps but were instead incorporated into the overall kinetic equation. As mentioned earlier, because this esterification reaction is reversible, the presence of water as a byproduct still affects the equilibrium position and indirectly influences the reaction rate as well as the triacetin produced (Sriratchachawan et al.,

2022). The stages of the esterification reaction between glycerol and acetic acid using a porous solid catalyst, under steady-state conditions, are illustrated in Figure 2 and presented in Equations (1) and (2) (Fogler, 2006).

$$N_{A \text{ ext}} = 3 N_{G \text{ ext}} = N_{A \text{ int}} = 3 N_{G \text{ int}} = \frac{dC_A}{dt} = 3 \frac{dC_G}{dt} \quad (1)$$

$$\begin{aligned} \frac{dC_A}{dt} &= k_{cA} (C_{A,b} - C_{A,s}) = D_{\text{eff},A} a_p \frac{dC_A}{dr} \\ &= k_1 C_A C_G - C_T C_W \end{aligned} \quad (2)$$

With, $N_{A \text{ ext}}$ and $N_{G \text{ ext}}$ =external diffusion rates of acetic acid and glycerol (mol/(dm³·s)); $N_{A \text{ int}}$ and $N_{G \text{ int}}$ =internal diffusion rates of acetic acid and glycerol (mol/(dm³·s)); C_A and C_G =concentrations of

acetic acid and glycerol at the catalyst active sites (mol/dm^3); C_T and C_W =concentrations of triacetin and water at the catalyst active sites (mol/dm^3); $C_{A,b}$ =concentration of acetic acid in the bulk liquid (mol/dm^3); $C_{A,s}$ =concentration of acetic acid at the external catalyst surface (mol/dm^3); k_{CA} =volumetric mass transfer coefficient of acetic acid ($1/\text{s}$); dC_A/dt and dC_G/dt =reaction rates of acetic acid and glycerol ($\text{mol}/(\text{dm}^3 \cdot \text{s})$); k_1 and k_2 =forward and reverse second-order rate constants ($\text{dm}^3/(\text{mol} \cdot \text{s})$); $D_{\text{eff},A}$ =effective diffusivity of acetic acid in the porous catalyst (dm^2/s); a_p =cross-sectional area available for diffusion within the particle pores (dm^2); dC_A/dr =radial concentration gradient of acetic acid inside the particle, from surface to center (mol/dm^4).

Research on triacetin has been conducted by many scholars and has advanced rapidly using a variety of methods. However, based on the literature reviewed, converting glycerol into triacetin is not straightforward. Even with different catalysts, the resulting selectivity for triacetin remains low. A sulfonated biochar catalyst derived from palmyra shell waste yielded only 4.20% triacetin selectivity (Jagadish et al., 2025), and a phosphate-silica catalyst from bamboo leaves produced just 24.00% triacetin selectivity (Manurung et al., 2022). A combination of porous alumina with Co/Ni/Mg metals achieved better triacetin selectivity of 53.00% (Bezerra et al., 2022). Microwave-irradiation studies using a Pd/activated carbon catalyst produced a high glycerol conversion of 96.64%, but the triacetin selectivity was very low at only 0.23% (Azmi et al., 2023). An interesterification system using babassu oil also yielded only 22.00% triacetin (Priebe et al., 2024). Increasing the temperature from 90°C to 110°C did increase acetic acid conversion, but triacetin selectivity remained very low at only 6.73% (Nuryoto et al., 2025). Some studies have achieved relatively high reactant conversion and triacetin selectivity (though still classified as low because they are below 70.00%), such as using mesoporous sulfonated carbon catalyst, which gave 97.00% glycerol conversion and 66.50% triacetin selectivity (Nda-Umar et al., 2020). A KIT-6 catalyst modified with $-\text{SO}_3\text{H}$ groups also showed reasonably good performance with 99.00% glycerol conversion, but triacetin selectivity was only 35.00% (Baingam et al., 2025). Referring to Figure 1, producing triacetin requires three reaction steps (formation of monoacetin, then diacetin, and finally triacetin), and each step generates water. Theoretically, the presence of water in the reaction

system tends to shift the equilibrium toward the reactants, preventing the reaction from proceeding fully to produce triacetin in significant amounts. Moreover, water has the simplest molecular structure compared with other substances (acetic acid, glycerol, monoacetin, diacetin, and triacetin), which have more complex structures and therefore larger molecular sizes than water. Because water molecules are smaller than the other compounds, they can diffuse more easily into the catalyst pores and occupy active sites, making it difficult for reactants such as glycerol and acetic acid to enter and react optimally within the catalyst. This condition hinders the esterification of glycerol and acetic acid to triacetin, as reflected by the consistently low triacetin selectivity. The low selectivity suggests that the reaction tends to remain at the intermediate stages, yielding mainly monoacetin and diacetin rather than proceeding further to triacetin. Even when esterification is conducted at a high molar ratio of up to 1:9 glycerol to acetic acid, triacetin selectivity remains low (Baingam et al., 2025). Therefore, an innovation is needed to address the problem of low triacetin selectivity. Studies on the esterification of glycerol and acetic acid have in fact been widely reported, but most of them still focus on catalyst development and the search for suitable reaction systems, so water control as a byproduct has not yet become a primary strategy for improving triacetin selectivity. This study proposes an innovation through in situ water removal as a process intensification and optimization strategy to increase the driving force of the reaction by shifting the equilibrium toward the products. Theoretically, this innovation has strong potential to improve the selectivity of the triacetin produced. To verify the success of this innovation, this study was conducted to evaluate the effect of in situ water removal on reaction performance in terms of acetic acid conversion and the resulting triacetin product. The findings can complement previous studies, enabling the development of an effective, efficient, and economical triacetin synthesis process that can be scaled up commercially and integrated with the biodiesel industry.

2. METHODOLOGY

2.1 Material and equipment

The main raw materials used in this study were technical-grade acetic acid (96%) and technical-grade glycerol (99%), both purchased from the Shopee Indonesia marketplace. The catalyst used was natural

clinoptilolite zeolite obtained from Lampung, Indonesia (LNZ) (Nuryoto et al., 2025; Hadi and Ilim, 2025; Hauli et al., 2025). Prior to use, the zeolite underwent pretreatment with 6 N H₂SO₄. This pretreatment was carried out to remove impurities, increase acidity, and enlarge the zeolite's surface area.

It is expected that, after pretreatment of the LNZ, diffusion-reaction processes in triacetin synthesis will proceed more rapidly, thereby maximizing triacetin yield. The equipment used for triacetin synthesis is illustrated in Figure 3.

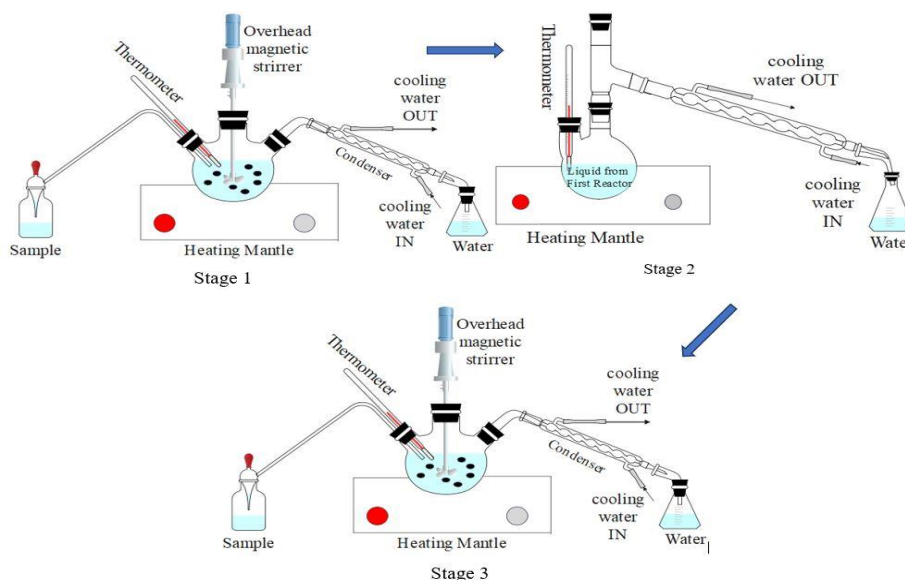


Figure 3. Schematic illustration of triacetin synthesis with in situ water removal

2.2 Natural zeolite catalyst preparation

Natural clinoptilolite zeolite from Lampung, Indonesia (LNZ), with a particle size of -45+60 mesh, was activated using a 6 N sulfuric acid solution, prepared by diluting 98% Merck sulfuric acid in distilled water to the desired volume, at a ratio of 10 g zeolite per 100 mL acid solution. The activation was carried out at 110°C for 2 h with stirring at 600 rpm (Nuryoto et al., 2025). The activated zeolite was then filtered and washed with distilled water until the pH of the wash water matched that of the distilled water. Next, the zeolite (LNZ) was drained and placed in an oven at 200°C for 2 h (Nuryoto et al., 2025). After cooling to room temperature, it was ready for use as a catalyst. To confirm that the activation had proceeded properly and that the zeolite was suitable for catalytic use, the LNZ was characterized before and after activation by X-ray diffraction (XRD) to observe changes in its crystal structure.

2.3 Esterification procedures

2.3.1 Stage 1 (preliminary reaction)

Glycerol and acetic acid in specified volumes, corresponding to reactant ratio of 1:3-1:5 mol glycerol

per mol acetic acid, were heated separately, with acetic acid in a beaker and glycerol in the reactor, until they approached the desired reaction temperature of 100°C (Sandid et al., 2024; Nuryoto et al., 2025). Cooling water was circulated through the condenser to condense the water vapor generated during the reaction, thereby ensuring that the removed water did not interfere with the experiment. Once both reactants reached a temperature close to the reaction set point of 100°C, the acetic acid was added to the reactor. The reaction temperature was then maintained at 100°C while overhead stirrer operated at 700 rpm (Nuryoto et al., 2025). After the mixture appeared homogeneous, a sample was collected for initial acid analysis (A_0) using 0.5 N NaOH, which was taken as the start of the reaction ($t_0=0$ h). The catalyst was then added to the reactor at 5% of the acetic acid mass (Sandid et al., 2024; Nuryoto et al., 2025). Subsequent samples were taken every hour for residual acid analysis (A_t) until the total reaction time reached 4 h. Acetic acid conversion was then calculated using Equation (3).

$$\% A = \frac{(A_0 - A_t)}{A_0} \times 100\% \quad (3)$$

With, %A=acetic acid conversion (%); A_0 =concentration of acetic acid at $t=0$ hours (mg/dm^3); A_t =concentration of acetic acid at time t hours (mg/dm^3).

2.3.2 Stage 2 (evaporation)

For Stage 2, the liquid product obtained from the preliminary reaction in Stage 1 under the optimal conditions was transferred to a two-necked flask and heated to evaporate the residual water from the mixture. The evaporation was carried out at 105°C and stopped when no more bubbles were observed, indicating that the residual water had evaporated.

2.3.3 Stage 3 (main reaction)

When the evaporation process was completed, the experiment proceeded to Stage 3, which was the main reaction, conducted at reaction temperatures of 90 , 100 , and 110°C . At this stage, the liquid from Stage 2, containing residual glycerol, acetic acid, monoacetin, diacetin, and triacetin, was further reacted with acetic acid using the optimal reactant ratio determined in the preliminary reaction. Samples were collected every hour over a total reaction time of 4 h. The sampling procedure and the method used to analyze and calculate acetic acid conversion were the same as those used in the preliminary reaction. In Stage 3, the triacetin product was analyzed by Fourier Transform Infrared Spectroscopy (FTIR) and validated by Gas Chromatography-Mass Spectrometry (GC-MS). The repeated reaction under water free conditions in Stage 3 was intended to promote the conversion of monoacetin, diacetin, and the remaining glycerol into triacetin (Figure 1).

2.4 Characterization of zeolite and analysis of the triacetin product

Characterization of the natural zeolite (LNZ) was carried out using a Bruker D8 ADVANCE X-ray Diffraction (XRD) instrument operated over a 2θ range of approximately 3° to 150° to identify changes in crystal structure. The product obtained from the main reaction (Stage 3) was analyzed by Fourier Transform Infrared Spectroscopy (FTIR) using an Alpha II instrument from Bruker, Germany, to identify changes in functional group peaks by comparison with standard references. This analysis served as an initial confirmation of whether the reaction had occurred and produced the expected product. Once the FTIR results indicated product formation, GC-MS analysis was performed for validation and to determine the percentage of triacetin produced. The GC-MS used was a thermo scientific instrument consisting of a

Trace 1,310 gas chromatograph and a Trace ISQ7000 mass spectrometer to identify triacetin and its byproducts, namely monoacetin and diacetin.

2.5 Mathematical model testing

To obtain more comprehensive information, this study also included reaction-kinetics calculations using a simple mathematical model, namely a pseudo-homogeneous model that was previously shown to be suitable for describing the reaction behavior, although the earlier study did not involve in situ water removal (Nuryoto et al., 2025). The use of the same mathematical model in this study was intended to test whether it remains valid under different conditions. If the model remains valid under different operating conditions, it may be used for reactor design and to predict conversion and product yield within specified operating ranges. The mathematical model was formulated based on several assumptions: (a) The catalyst particles were assumed to be small and uniform in size; (b) acetic acid was present in excess, so the reverse reaction was neglected; (c) the reaction rate was based on the change in acetic acid concentration; and (d) external and internal diffusion, as well as adsorption and desorption, were assumed to occur rapidly without significant resistance, so the reaction step was taken as the rate controlling step of the overall process. Based on these assumptions and the pseudo-homogeneous model, the concentrations of reactants and products in Equation (2) are taken to be equal to those in the bulk liquid phase, thus Equation (2) can be simplified into Equation (4).

$$\frac{dC_A}{dt} = k C_A^n \quad (4)$$

Where; dC_A/dt =acetic acid reaction rate ($\text{mol}/(\text{dm}^3 \cdot \text{h})$); k =reaction rate constant ($1/\text{h}^n$); n =reaction order; C_A =acetic acid concentration at a certain time (mol/dm^3).

This study employed reaction orders $n=1$ and $n=2$, which are commonly applied in chemical reactions, with $n=1$ or 2. Equation (4) can be rewritten as Equations (5) and (6).

$$-\frac{dC_A}{dt} = k C_A \quad (5)$$

$$-\frac{dC_A}{dt} = k C_A^2 \quad (6)$$

Equations (5) and (6) can be integrated to obtain Equations (7) and (8).

$$\ln C_A = \ln C_{A0} + k t \quad (7)$$

$$\frac{1}{C_A} = \frac{1}{C_{A0}} + k t \quad (8)$$

The parameter (k) was determined by fitting the experimental data to first- and second-order kinetic models. The model with an R^2 value close to 1 is considered suitable for predicting acetic acid conversion under different operating conditions and for future reactor design.

3. RESULTS AND DISCUSSION

3.1 LNZ catalyst characterization

The XRD diffraction pattern of the natural zeolite (LNZ) before activation showed higher peak intensities than after activation using 6 N H_2SO_4 (Figure 4, green circled area). This decrease in peak intensity indicates that changes in the crystalline structure occurred as a result of the dealumination process. The observed changes in intensity and crystalline structure in Figure 4 show that the pretreatment of LNZ with H_2SO_4 altered the aluminosilicate framework of the zeolite. This

phenomenon is consistent with what is illustrated in Figure 5, where protons from H_2SO_4 attack the aluminosilicate framework and cause the release of Al atoms from the tetrahedral structure of the zeolite. Thus, Figure 4 provides structural evidence, while Figure 5 explains the chemical mechanism underlying these changes, so the two figures complement each other in supporting the occurrence of dealumination. This dealumination process contributes significantly to the increase in the Si/Al ratio, which is directly associated with the enhancement of the acidity of the LNZ catalyst. Referring to the study by Nuryoto et al. (2025), which used the same type of zeolite and activation conditions, treatment with 6 N H_2SO_4 increased the specific surface area from 57.230 m^2/g to 98.738 m^2/g and also showed stronger acidity characteristics based on TPD NH_3 analysis, with desorption peaks detected up to 400°C. The increase in surface area and acidity indicates that the activated LNZ has better catalytic potential when used in the esterification reaction.

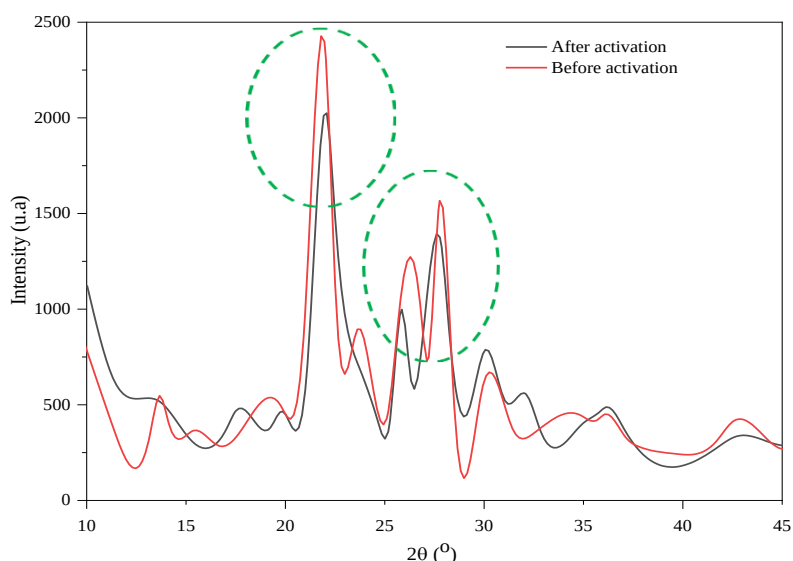


Figure 4. XRD characterization of LNZ zeolite before and after activation with 6 N H_2SO_4

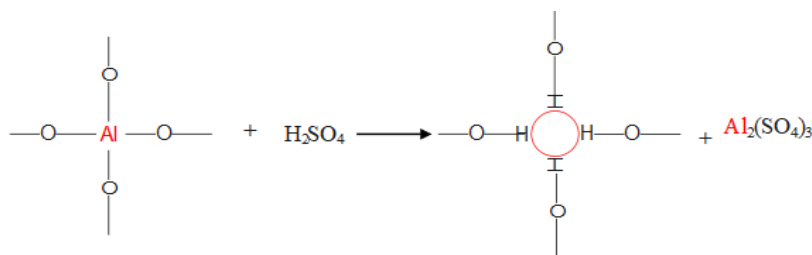


Figure 5. Illustration of dealumination reaction of natural zeolite using H_2SO_4 (Feng et al., 2019)

3.2 Effect of reactant ratio

Increasing the reactant ratio led to an increase in acetic acid conversion (Figure 6). At glycerol-to-acetic acid molar ratios of 1:3, 1:4, and 1:5, the acetic acid conversions after 4 h were 92.00%, 94.40%, and 97.60%, respectively. Theoretically, increasing the amount of acetic acid beyond the stoichiometric requirement increases its concentration in the reaction system, which can enhance mass transfer and adsorption at the catalyst active sites, thereby increasing the overall reaction rate (Equations 1 and 2). From a thermodynamic perspective, the phenomenon shown in Figure 6 is logical. As the reactant ratio increases, the reaction equilibrium constant (K_e) also increases (Equation 9) (Fogler, 2006). An increase in acetic acid concentration (C_A) proportionally raises k_1 and thereby increases K_e . A

higher k_1 leads to higher acetic acid conversion and greater product formation.

$$K_e = \frac{k_1}{k_2} = \frac{C_A^3 C_G}{C_W^3 C_T} \quad (9)$$

With, C_A , C_G , C_T , and C_W =concentrations of acetic acid, glycerol, triacetin and water (mol/dm³); 3=stoichiometry coefficient (dimensionless); K_e =equilibrium constant (dimensionless).

Thus, increasing the moles of acetic acid relative to glycerol, as shown in Figure 6, creates reaction conditions that drive the reaction toward product formation while minimizing the reverse reaction (Figure 1). Under these conditions, the forward reaction rate becomes dominant over the reverse reaction, resulting in higher overall reactant conversion (Hilmioğlu, 2022).

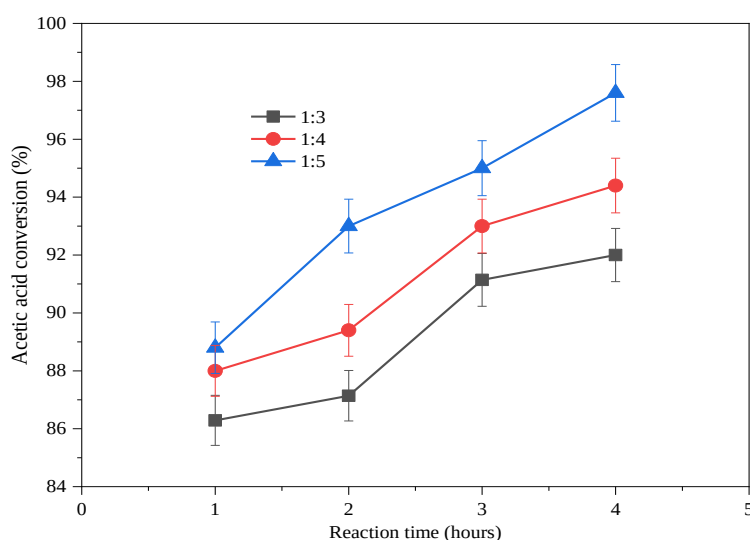


Figure 6. Effect of reactant ratio (mol glycerol/mol acetic acid) at a reaction temperature of 100°C (preliminary reaction)

Table 1 shows that increasing the reactant ratio (mol glycerol/mol acetic acid) leads to higher glycerol conversion. However, although glycerol conversion is relatively high, exceeding 90.00%, triacetin selectivity remains low, at only 8.00% and 36.40% (Baingam et

al., 2025; Doukeh et al., 2025). This phenomenon is likely due to the presence of water in the reaction system, which shifts the equilibrium and limits triacetin formation.

Table 1. Effect of reactant ratio (mol glycerol/mol acetic acid) on triacetin synthesis from acetic acid and glycerol

No.	Operation condition	Reactant conversion-triacetin selectivity	Reference
1	Reactant ratios of 1:3, 1:6, and 1:9, a reaction temperature of 115°C, a reaction time of 8 h.	Glycerol conversions were 91.0%, 99.0%, and 100.0%, with triacetin selectivity of 36.4% (overall reactant conversion reached 100%).	Baingam et al. (2025)
2	Reactant ratios of 1:3 and 1:3.6 (mol/mol) at 100°C for 4 h, using an SnFe ₂ O ₄ catalyst.	Glycerol conversion increased from 55.0% to 90.0%, while triacetin selectivity rose from 1.0% to 8.0%.	Doukeh et al. (2025)
3	Reactant ratios of 1:6 and 1:9, a reaction temperature of 110°C, and a reaction time of 150 min.	Glycerol conversion increased from 78.0% to 87.0%.	Petchsoongsakul et al. (2025)

3.3 Effect of reaction temperature

Acetic acid conversion increased as the reaction temperature increased. At 90, 100, and 110°C after 4 h of reaction, the conversions were 85.00%, 90.00%, and 94.00%, respectively (Figure 7). This behavior can be attributed to the increase in molecular kinetic energy at higher temperatures, which leads to more frequent and energetic collisions between reactant molecules. As a result, the reaction rate increases, leading to higher acetic acid conversion. The effect of temperature on collision frequency and reaction rate is described by Equations (10) and (11) (Fogler, 2006).

$$k = A e^{-\frac{E_a}{RT}} \quad (10)$$

$$A = p N_a \pi d^2 \sqrt{\frac{8 k_B T}{\pi \mu}} \quad (11)$$

With, k =reaction rate constant (first order=1/h; second order= $\text{dm}^3/\text{mol}\cdot\text{s}$); A =collision frequency factor (first order=1/s ; second order= $\text{dm}^3/\text{mol}\cdot\text{s}$); E_a =activation energy (J/mol); R =universal gas constant (8.314 J/(mol·K)); T =temperature (K); p =probability factor (dimensionless); N_a =Avogadro's number (6.022×10^{23} 1/mol); π =3.14 (dimensionless); d =molecular diameter (dm); k_B =Boltzmann constant (1.3806×10^{-23} J/K); and μ =reduced mass of the two colliding molecules (kg).

According to Equations (10) and (11), together with Equation (2), increasing the reaction temperature has a positive effect on the reaction rate, but only up to a certain limit. For a liquid-liquid reaction such as that in this study, the reaction temperature should not exceed the boiling point of either reactant, particularly acetic acid at 118°C. At temperatures above this point, contact between glycerol and acetic acid can decrease sharply because the two reactants exist in different phases, with acetic acid in the vapor phase and glycerol in the liquid phase. As a result, molecular interactions between the reactants are greatly reduced, even though such interactions are essential for the reaction to occur. If the reaction is conducted well above the boiling point, sufficient interaction can only be maintained by using a high reactant ratio and operating under reflux. For example, a reaction temperature of 130°C can produce up to 99.00% glycerol conversion, but it requires a glycerol-to-acetic acid molar ratio of 1:9 (Sandid et al., 2024). However, such operating conditions have several drawbacks, including relatively high reactant consumption, greater separation loads, and the need for an additional condenser to return acetic acid vapor to the reactor under reflux. Therefore, a process employing both high reaction temperatures and high reactant ratios becomes uneconomical.

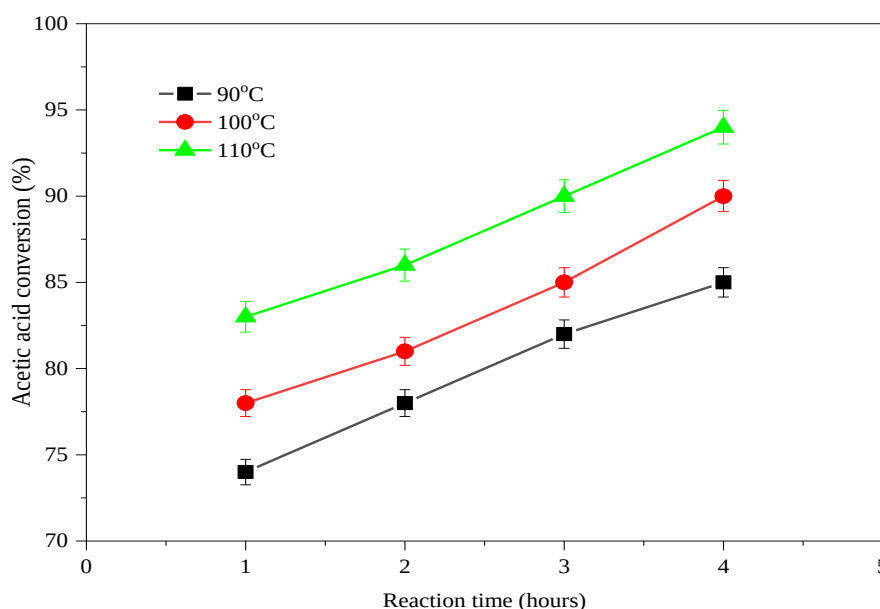


Figure 7. Effect of reaction temperature on acetic acid conversion (main reaction)

The trend observed in this study is consistent with previous research (Table 2), showing that increasing the reaction temperature leads to higher

reactant conversion. However, at lower temperatures below 90°C (25-65°C), glycerol conversion remains relatively low, at about 5-55%, while triacetin

formation remains limited to only 0-5% (Da Silva et al., 2025). This indicates that the reaction has not proceeded efficiently because the thermal energy is still insufficient to overcome the activation energy barrier effectively, so the reaction products are dominated by the intermediates monoacetin and diacetin rather than triacetin. When the reaction temperature is increased to 90-110°C under the specified operating conditions, with glycerol-to-acetic

acid molar ratio of 1:6, glycerol conversion increases significantly from 58.56% to 66.38% (Setyaningsih et al., 2018). This result confirms that, in addition to reactant ratio, reaction temperature is a key factor in triacetin synthesis. Higher temperatures increase the frequency of effective collisions between glycerol and acetic acid molecules, thereby increasing the esterification rate and driving the reaction toward triacetin formation.

Table 2. Effect of reactant ratio on triacetin synthesis from acetic acid and glycerol

No.	Operation condition	Reactant conversion-triacetin selectivity	Reference
1	Reaction temperatures of 25 to 65°C, catalyst $\text{Sn}_2\text{SiW}_{12}\text{O}_{40}$, glycerol-to-acetic acid molar ratio 1:3, catalyst loading 0.1 mol%, and reaction time of 6 h.	Glycerol conversions were 5%, 15%, 20%, 5%, and 55%, with triacetin formation of 0%, 0%, 0%, 3%, and 5%, respectively.	Da Silva et al. (2025)
2	Reaction temperatures of 90 to 110°C, reactant ratio 1:6 (mol glycerol/mol acetic acid), reaction time 90 minutes, catalyst concentration 3 wt%, and stirring speed 175 rpm.	Glycerol conversions were 58.56%, 66.91%, and 66.38% at 90, 100, and 110°C, respectively.	Setyaningsih et al. (2018)

3.4 Analysis of reaction products

Based on reference FTIR data for pure glycerol (National Institute of Standards and Technology, 2025a), glycerol exhibits a strong O-H absorption band in the range of 3,000-3,700 $1/\text{cm}$ (Akachat et al., 2025), with transmittance approaching 1%, and no distinct C=O absorption band characteristic of esters in the range of 1,702.42-1,740 $1/\text{cm}$ (Akachat et al., 2025; Aisyah et al., 2021). When glycerol was reacted with acetic acid in this study and analyzed by FTIR at 100°C and 110°C, the O-H absorption band in the range of 3,000-3,700 $1/\text{cm}$ became markedly weaker, with transmittance increasing from about 1% to

approximately 80% (Figure 8, orange circle). In addition, in the region 1,702.42-1,740 $1/\text{cm}$ (green circle), which is characteristic of esters, distinct peaks appeared in the samples obtained at 100°C and 110°C, with transmittance of around 20% (green circle). These results indicate the formation of esters products, namely monoacetin, diacetin, and triacetin. Compared with the standard FTIR spectrum (National Institute of Standards and Technology, 2025b), the FTIR results shown in Figure 8 are consistent with triacetin. The peak in the red circled region of Figure 8 (960-970 $1/\text{cm}$) is sharper at 110°C than at 100°C.

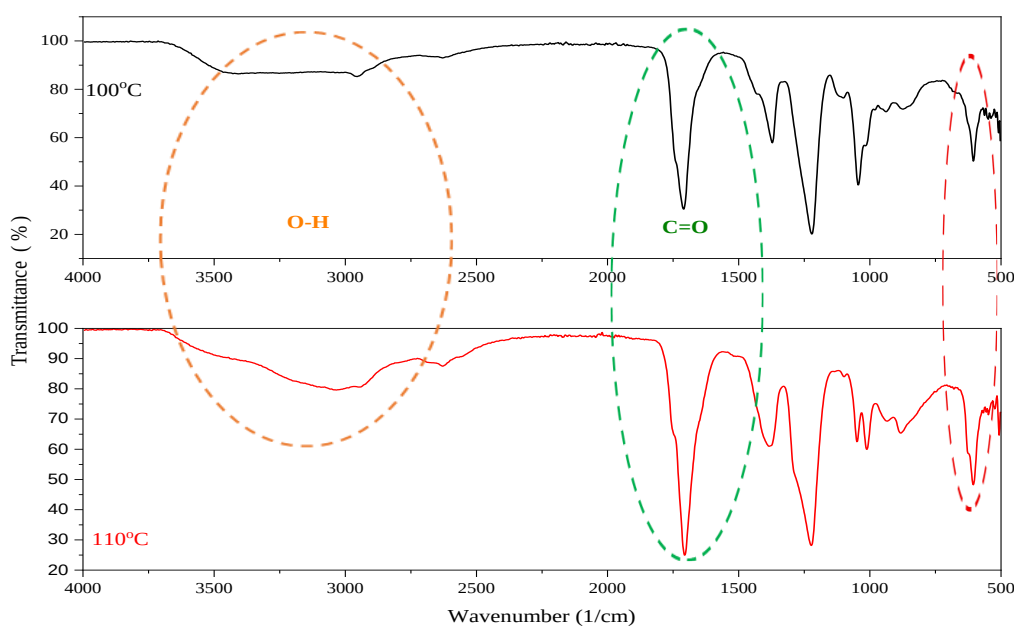


Figure 8. FTIR results at 100°C and 110°C for a 1:5 glycerol-to-acetic acid molar ratio

To validate the FTIR results, the contents of monoacetin, diacetin, and triacetin were analyzed using GC-MS (Figure 9(a) and Figure 9(b)). Triacetin selectivity relative to monoacetin and diacetin was 79.98% at a reaction temperature of 100°C (Figure 9(a)) and increased to 85.58% at 110°C (Figure 9(b)), representing an increase of 5.60%. These results indicate that increasing the reaction temperature at a reactant ratio of 1:5 mol acetic acid, together with in situ water removal during the reaction, promotes triacetin formation. Compared with a previous study

conducted without in situ water removal (Nuryoto et al., 2025), triacetin selectivity at 100°C was only 6.73%, whereas under the same temperature in this study it reached 79.98%. These findings support the hypothesis that the presence of water in the reaction system is a key factor limiting the esterification of glycerol and acetic acid to triacetin. Therefore, the in situ water removal strategy in this study proved effective, resulting in a substantial increase of 73.25% in triacetin selectivity compared with the previous study (Nuryoto et al., 2025).

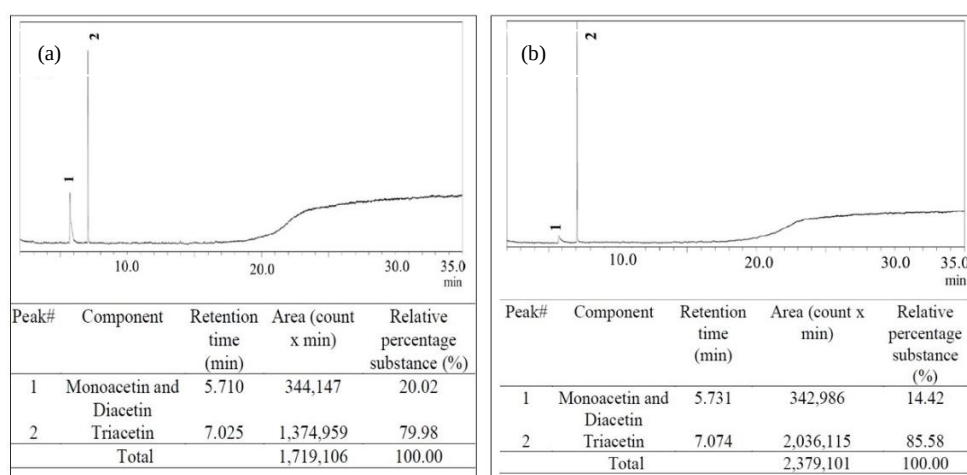


Figure 9. GC-MS results: (a) at 100°C and (b) at 110°C

3.5 Mathematical model testing

Based on Figures 10(a) and 10(b), the second-order mathematical model provides a better fit than the first-order model, as indicated by coefficients of determination (R^2) that are closer to 1. For the second-order model, the R^2 values are above 0.94562, whereas the highest R^2 for the first-order is only 0.84343. Therefore, the second-order kinetic model is more representative of the reaction behavior in the esterification of glycerol and acetic acid for triacetin synthesis. Previous research by Nuryoto et al. (2025) also showed that the second-order model performs better than the first-order model based on R^2 values. This indicates that the second-order pseudo-homogeneous model is suitable for predicting reactant conversion during operation and for reactor design. Using the best fit model (second-order pseudo-homogeneous), the reaction rate constant (k) at each temperature was determined (Table 3). The obtained k values and the corresponding temperatures (T) were then used to construct a plot of $\ln k$ versus $1/T$ according to the Arrhenius equation (Equation 10), as shown in Figure 11. This plot was used to determine

A (the molecular collision frequency factor) and E_a (the activation energy), since both parameters are important for reactor operation and design.

From the linearization of Table 3 (see Figure 11), Equation (12) was obtained.

$$\ln k = 17.89403 - \frac{7341.42499}{T} \quad (12)$$

Referring to Equation (12) and using the gas constant $R=8.314 \text{ J/ (mol} \cdot \text{K)}$, the collision frequency factor (A) was calculated to be $5.91 \times 10^7 \text{ dm}^3/(\text{mol} \cdot \text{h})$, and the activation energy (E_a) was $6.10 \times 10^4 \text{ J/mol}$. This E_a value is quite similar to that reported in a previous study by Nuryoto et al. (2011), which used a different catalyst, namely Indion 225 Na, without in situ water removal, and reported an E_a of $6.60 \times 10^4 \text{ J/mol}$. The observed difference may be attributed to differences in catalyst concentration and activity. In this study, the catalyst used was activated natural clinoptilolite zeolite at 5% relative to the acetic acid mass, whereas the previous study used an ion-exchange catalyst (Indion 225 Na) at 3% of the acetic acid mass (Nuryoto et al., 2011).

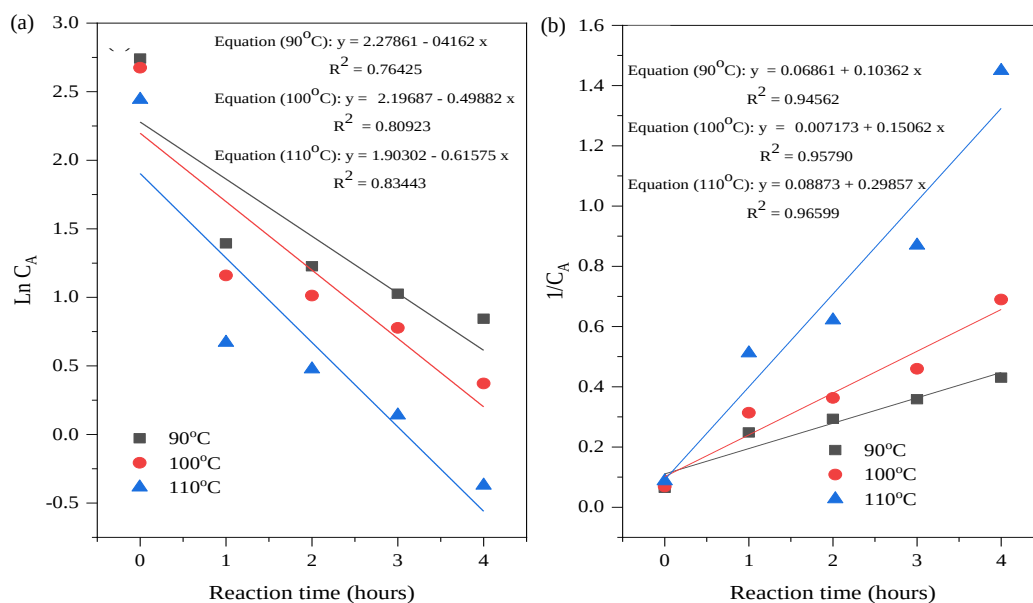


Figure 10. Model validation: (a) first-order pseudo-homogeneous model and (b) second-order pseudo-homogeneous model.

Table 3. Reaction rate constant (k) versus reaction temperature

No.	T (K)	k	1/T	ln k
1	363.15	0.10362	0.0027537	-2.26702
2	373.15	0.15062	0.0026799	-1.89300
3	383.15	0.29857	0.0026099	-1.20875

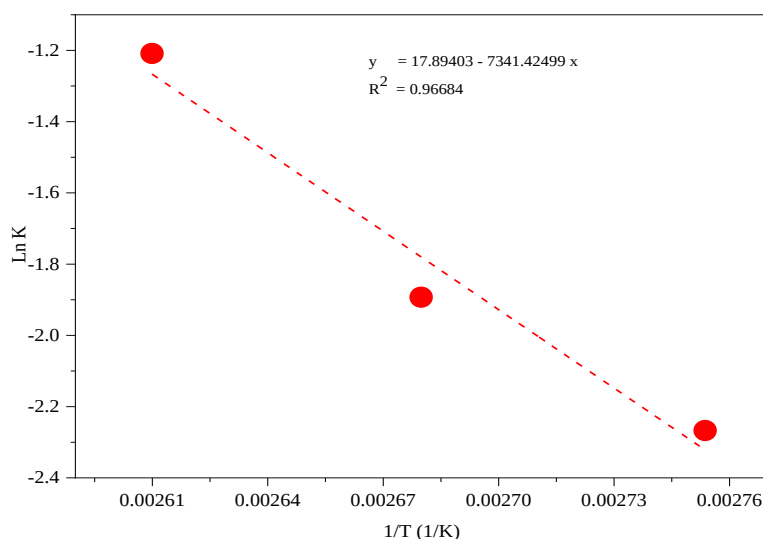


Figure 11. Linearization of $\ln k$ versus $1/T$ for the second-order model

3.6 Practical implication and implementation strategy

In general, the optimization results and kinetic modeling presented in this study provide a strong scientific basis for the development of triacetin synthesis through reaction intensification via in situ water removal. This approach enables the reaction

equilibrium to shift continuously toward product formation, thereby increasing glycerol conversion and triacetin selectivity without requiring extreme operating conditions. In the next stage of development, this research has the potential to be expanded to pilot scale by considering reactor design, long-term catalyst stability, and cyclic performance

evaluation of the water removal system. Techno-economic assessment (TEA) and life cycle assessment (LCA) are also needed to evaluate its commercial feasibility and environmental impact compared with conventional processes. From an industrial perspective, integration of this process into the biodiesel production chain has significant potential because it converts glycerol, the main byproduct, into value-added triacetin as a biodiesel fuel additive. Therefore, this study not only contributes to the development of kinetic models but also offers a direction for implementing a more efficient, economical, and sustainable.

4. CONCLUSION

This study shows that the in situ water removal strategy applied during the reaction through a three-stage esterification of glycerol with acetic acid, significantly improved reaction performance. The best operating conditions were obtained at glycerol-to-acetic acid molar ratio of 1:5 and a reaction temperature of 110°C, yielding 94.00% acetic acid conversion and 85.58% triacetin selectivity. These results indicate a shift in product distribution from monoacetin and diacetin toward the desired main product, triacetin, and confirm the importance of reaction temperature, reactant ratio, and water removal from the system in increasing both acetic acid conversion and triacetin selectivity. Kinetic analysis showed that the second-order pseudo-homogeneous model provided a better fit to the data than the first-order model, with R^2 values above 0.94562, a frequency factor (A) of $5.91 \times 10^7 \text{ dm}^3/(\text{mol} \cdot \text{h})$, and an activation energy (E_a) of $6.10 \times 10^4 \text{ J/mol}$. The results of this study strengthen the theoretical foundation while also providing guidance for reactor design and process operation. From an industrial application perspective, the conversion of glycerol into triacetin has the potential to increase added value within the biodiesel production chain while also supporting the implementation of green chemistry principles. Therefore, this research is worthy of further development at the pilot scale for process validation, although additional evaluation is still needed, including catalyst stability, energy efficiency analysis, and integration with biodiesel production units, in order to support commercialization readiness and contribute to reducing the carbon footprint.

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AUTHOR CONTRIBUTIONS

Nuryoto Nuryoto: Conceptualization, methodology, supervision, visualization, and writing-original draft preparation and finishing; Nasywa Hanifah and Najiha Hariani: Investigation, validation, resources, and data curation; Rafiif Nur Tahta Bagaskara: Writing-review and editing.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Decadal Rainfall Distribution Shift in Northern Coastal Java: Histogram-Based Clustering Using Observations and CHIRPS

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ABSTRACT

Coastal lowlands are highly vulnerable to seasonal changes and rainfall variability, which affect the risk of floods and droughts. Therefore, this study aimed to analyze decadal changes in the monthly rainfall distribution along the northern coast of Central Java (Pantura), using data from 51 stations of the Meteorology, Climatology, and Geophysics Agency (BMKG) and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) v2.0. A smoothed histogram was used to calculate the probability density of rainfall for each decade. Subsequently, the distribution between decades was compared using 6 metrics to assess distribution displacement, divergence, overlap, and shift in peak, centroid, and width. The level of uncertainty was measured using the bootstrap method at confidence levels of 5%, 10%, and 25%. The six metrics were normalized and combined into a single composite index called the Total Normalized Index (TNI). K-means clustering was then applied to map changes according to the same rainfall patterns. Analysis of both sources showed a gradient pattern from west to east. Rainfall was concentrated in the west, with moderate changes in structure in the central area, and a more dispersed rainfall pattern with high variability in the east, particularly from 2011 to 2020. CHIRPS data recorded the regional trends but tended to cloud out local fluctuations. This study contributed to new investigations since the implementation of histogram-based rainfall distribution analysis into a composite index. The application of this method as part of a spatial clustering model was proposed to map alterations in rainfall distribution each decade. The method also helped in evaluating coastal climate risk and adaptation planning.

HIGHLIGHTS

- Six distribution metrics show an apparent decadal shift in rainfall structure across Pantura.
- Observations and CHIRPS show consistent west-east gradients in rainfall change.
- TNI confirms significant long-term rainfall transformation in both datasets.
- K-means clustering delineates spatially coherent clusters of rainfall change.
- Recent decades show an eastward shift in rainfall variability signals.

1. INTRODUCTION

The hydrological cycle is enhanced by global warming, which causes more moisture in the atmosphere and risks of causing heavy rainfall (Xiong and Yang, 2024). Consistent with the Clausius-Clapeyron relationship, which describes an approximate 7 percent increase in atmospheric water holding capacity per one degree Celsius warming, rainfall extremes are expected to intensify.

Meanwhile, the variations will be spatially heterogeneous across different areas. This tendency is supported by the Intergovernmental Panel on Climate Change report, which documents rainfall increases in humid tropical areas and high latitudes, while rainfall decreases occur in dry subtropical areas (Li et al., 2025; Parmesan et al., 2023). The spatial-temporal changes also increase the risk of hydrometeorological events, such as floods,

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landslides, and droughts, particularly in susceptible areas, including Central Java (Putri et al., 2022).

The Asian and Australian responses to climate in the area were complex. Monsoon rainfall has been reported to increase significantly in intensity in South and Southeast Asia (Varghese et al., 2025). During the last 70 years, the rainfall in India has tripled (Roxy et al., 2017). However, southern Australia has experienced a significant decline in seasonal rainfall due to anthropogenic factors (McKay et al., 2023). Climate variability, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), influences decadal anomalies, as observed in Indonesia (An et al., 2023; Pillai et al., 2021; Supari et al., 2018).

A clear example of high climate vulnerability is the northern coastal area of Central Java (Pantura). Due to its low topography, the Pantura area is vulnerable to potential hydrometeorological disasters, which are worsened by rapid urbanization and its sensitivity to monsoon variability. Several studies show that the rainy season is characterized by high rainfall intensity, and the dry season is prolonged, with flooding occurring more than 70% of the time between January and March. There was also an accumulation of monthly rainfall exceeding 1,000 mm (Agusta and Putri, 2023; Handayani et al., 2020). These hydrometeorological dynamics show the importance of analyzing decadal-scale spatial and temporal distributions.

Histogram-based distribution diagnostics and coastal-scale clustering have rarely been applied in Pantura, Central Java, despite related studies in other areas (Australia, Panama, Turkey) (Handayani et al., 2020; Hatvani et al., 2025; Kömüschü et al., 2022). In Indonesia, recent studies documented changes in rainfall frequency and intensity, but without integrating histogram metrics with local coastal clustering, as well as jointly analyzing station data and CHIRPS in this framework (Pattipeilohy et al., 2024; Pertiwi et al., 2024; Kurnianingsih et al., 2025; Funk et al., 2015). This study assesses the decadal (1991-2020) shift in monthly rainfall distribution using 51 BMKG stations and CHIRPS, combining six distribution metrics into a Total Normalized Index (TNI) and applying K-means to map spatial transformation patterns relevant to climate adaptation.

Operational in detecting decadal changes in rainfall distribution, this study evaluates three testable hypotheses that can be associated with each distribution metric:

- H1: Decadal changes are evident from the shift in the peak of rainfall intensity and the centroid of the distribution, as well as the decrease in distribution overlap.

- H2: Rainfall variability tends to widen in recent decades, as reflected in the increased distribution width and the distance between decades.

- H3: The transformation of rainfall distribution shows a coherent west-central-east gradient pattern, which can be identified through the TNI and K-means clustering.

2. METHODOLOGY

2.1 Data source

This study analyzed monthly rainfall data from 51 rain gauge stations owned by the Meteorology, Climatology, and Geophysics Agency (BMKG) along the North Coast of Central Java (Pantura) during the period 1991-2020 (Figure 1). As grid-based comparative data, this study used monthly rainfall from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) version 2.0 with a spatial resolution of 0.05° (UCSB, 2025; Funk et al., 2015). CHIRPS data from 1991-2020 were downloaded from the Climate Hazards Center portal (<https://data.chc.ucsb.edu/products/CHIRPS-2.0/>) and processed in Python, then bilinearly interpolated at BMKG station areas from the four nearest grids.

The handling of missing data has been predetermined, and months with anomalous data due to station damage are treated as missing. Only the decade-station data series with $\geq 90\%$ monthly values were used in the analysis, while the rest were excluded from the distribution estimation. No temporal imputation was applied, and CHIRPS pixels with NoData status were also excluded (Afrifa-Yamoah et al., 2020).

2.2 Decadal segmentation

The 30-year dataset was segmented into three decades, namely (1) 1991-2000, (2) 2001-2010, and (3) 2011-2020. This division followed a climatological framework that used 30 years as the basis for climate conditions, with updates every 10 years (WMO, 2017). Each ten-year period contained 120 months, which enabled analysis of rainfall patterns using an equal sample size while focusing on long-term changes and minimizing the influence of individual events. Two comparative periods were constructed, namely Decade-a: 2001-2010 vs 1991-2000; and Decade-b: 2011-2020 vs 2001-2010. The

decade-to-decade assessment was also made available by the use of the adjacent decades, with a provision for a stable evaluation of progressive changes in the

rainfall distribution patterns and variability in both observations and CHIRPS.

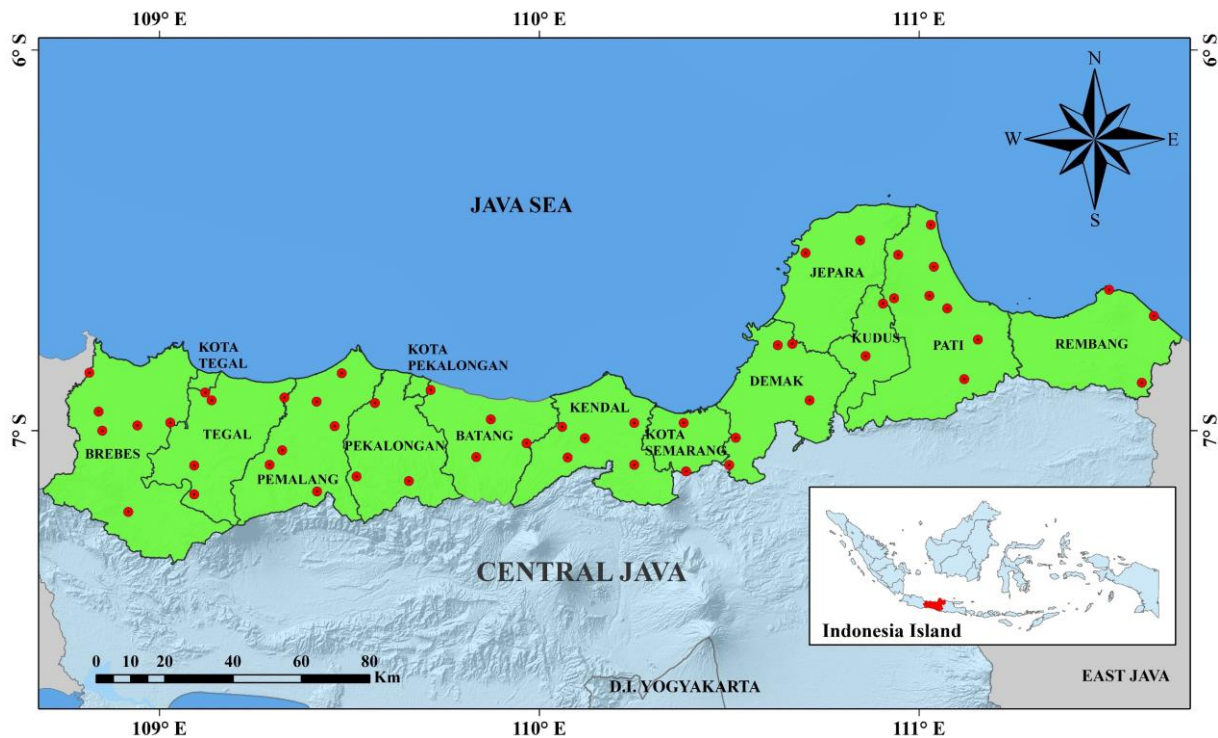


Figure 1. Area of BMKG observation stations across the North Coast of Central Java (Pantura)

2.3 Probability distribution estimation

The probability distribution of each decade and station estimated with a smoothed histogram were used to evaluate decadal changes in rainfall patterns (Figure 2). This measure provided a strong representation of distributional shape and showed lower sensitivity to extreme values. The resulting density curves would serve as a source to assess changes in the intensity of the peaks in terms of the width distribution and general displacement across decades.

The use of histograms in the current study, rather than a single parametric fit and kernel density estimation (KDE), was due to the fact that aggregates of precipitation were constrained to 0 and often skewed to the right. However, the adequacy of a given parametric distribution varied across datasets and aggregation periods. KDE was highly sensitive to bandwidth choice, as insufficient smoothing introduced local spurious features, while excessive smoothing obscured significant distributional structure. In comparison, a histogram built with an objective data-based rule of bin-width gives a clear and repeatable foundation on which to base inter-

decadal comparison of distributional morphology (Freedman and Diaconis, 1981; Jones et al., 1996; Svensson et al., 2017).

A histogram was plotted using the same bin edges for a given station, with two decades of monthly data combined to determine the bin edges, facilitating direct results comparison. A bin width was objectively defined with the help of the Freedman-Diaconis rule, $h=2IQRn^{-1/3}$, taking into consideration the interquartile range and the size of the sample. The counts in each of the bins were then translated into a probability density with a cumulative total of 1, and the outcome was smoothed using a Gaussian filter of width 1 bin. The x-axis of both density plots was the amount of rainfall in mm/month in a month, with the y-axis showing the probability density in units of 1/mm.

Statistical significance testing was carried out using bootstrap confidence intervals for each metric. Global curve difference tests, such as the Kolmogorov-Smirnov, were unnecessary because these methods showed general differences without providing details on specific changes in distributional features.

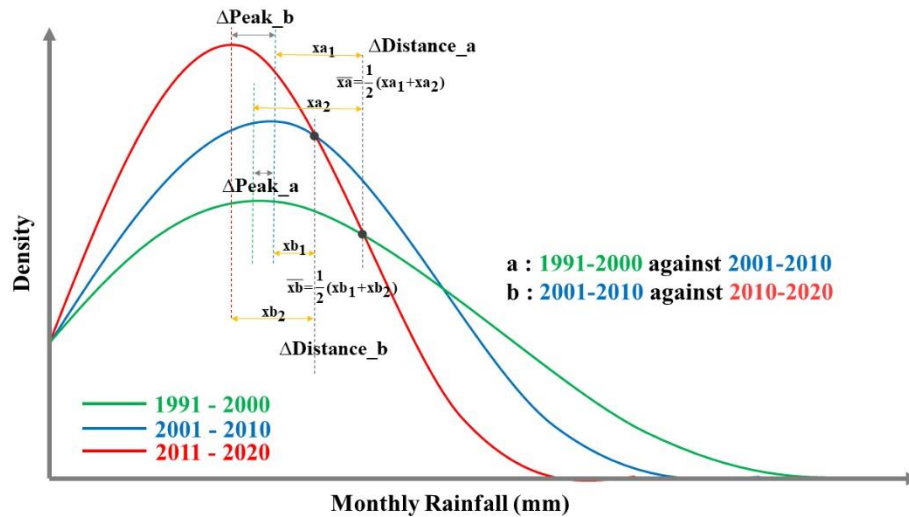


Figure 2. Illustration of histogram-based probability density estimation (x-axis: monthly rainfall; y-axis: probability density)

2.4 Distribution metrics

Six metrics (Table 1) were used to characterize inter-decadal variations. For brevity, these metrics were referred to as WD, KL, OVL, ΔPeak , $\Delta\text{Distance}$, and ΔWidth (Supplementary data).

- Wasserstein distance (WD) for overall displacement between distributions.
- Kullback-Leibler divergence (KL) for changes in distributional shape.
- Overlap coefficient (OVL) for similarity between decades.

- Peak shift (ΔPeak) for changes in predominant rainfall intensity.
- Centroid shift ($\Delta\text{Distance}$) for changes in the distribution mean (centroid).
- Width shift (ΔWidth) for changes in dispersion (standard deviation).

The metrics collectively captured changes in rainfall intensity, timing, and distribution morphology (Tolhurst et al., 2023; Magyar and Sambridge, 2023; Shen et al., 2025). Full mathematical formulations were provided in Supplementary data.

Table 1. Variables used to construct the TNI for two decadal comparisons: (a) 2001-2010 vs 1991-2000 and (b) 2011-2020 vs 2001-2010

Index component	Statistical description	Symbol	Unit	Climatological meaning
Wasserstein distance (WD)	Distribution displacement between decades	WD-a; WD-b	mm/month	General displacement of the monthly rainfall distribution
Kullback-Leibler divergence (KL)	Distributional divergence (shape difference)	KL-a; KL-b	unitless	Change in distribution shape between decades
Overlap coefficient (OVL)	Distributional similarity (overlap area)	OVL-a; OVL-b	Unitless (0-1)	Higher overlap shows a more stable distribution
Peak shift (ΔPeak)	Change in modal (peak) rainfall intensity	ΔPeak -a; ΔPeak -b	mm/month	Shift in the most frequent monthly rainfall level
Centroid shift ($\Delta\text{Distance}$)	Change in distribution centroid (mean)	$\Delta\text{Distance}$ -a; $\Delta\text{Distance}$ -b	mm/month	Shift in the center of mass of the rainfall distribution
Width shift (ΔWidth)	Change in dispersion (standard deviation)	ΔWidth -a; ΔWidth -b	mm/month	Broadening or narrowing of monthly rainfall variability
Total Normalized Index (TNI)	Composite index (equal-weight integration of six normalized metrics)	TNI-a; TNI-b	unitless	Integrated magnitude of decadal distributional change

All signed shift metrics are computed as the value in the later decade minus the value in the earlier decade.

2.5 Index Normalization and TNI Construction

The six-distribution metrics were calculated at each station to compare two pairs of decades, namely (a) 2001-2010 vs 1991-2000, and (b) 2011-2020 vs

2001-2010. Each metric was then normalized to a unitless scale of 0-1 using the min-max method. This normalization was carried out separately for the BMKG and CHIRPS datasets in each decade comparison.

Let $M_{i,c}$ denote the value of a given metric at station i for comparison $c \in \{a,b\}$. The normalized metric $M_{i,c}^*$ is defined as:

$$M_{i,c}^* = \frac{M_{i,c} - M_{\min,c}}{M_{\max,c} - M_{\min,c}} \quad (1)$$

Where; $M_{\min,c}$ and $M_{\max,c}$ are the minimum and maximum values across all stations within the same dataset and comparison period c .

The OVL decreases as distributional change strengthens, and reverse normalization ensures that larger values correspond to greater change:

$$OVL_{i,c}^* = 1 - \frac{OVL_{i,c} - OVL_{\min,c}}{OVL_{\max,c} - OVL_{\min,c}} \quad (2)$$

For signed shift metrics (ΔPeak , $\Delta\text{Distance}$, ΔWidth), the magnitude of change was used for index construction:

$$\Delta\text{Peak}_{i,c}^{\text{abs}} = |\Delta\text{Peak}_{i,c}|, \Delta\text{Distance}_{i,c}^{\text{abs}} = |\Delta\text{Distance}_{i,c}|, \Delta\text{Width}_{i,c}^{\text{abs}} = |\Delta\text{Width}_{i,c}| \quad (3)$$

Each magnitude term was then normalized using the same min-max scaling:

$$(\Delta^{\text{abs}})_{i,c}^* = \frac{\Delta_{i,c}^{\text{abs}} - \Delta_{\min,c}^{\text{abs}}}{\Delta_{\max,c}^{\text{abs}} - \Delta_{\min,c}^{\text{abs}}} \quad (4)$$

The TNI was computed as the aggregation (sum) of the six normalized metrics:

$$TNI_{i,c} = WD_{i,c}^* + KL_{i,c}^* + OVL_{i,c}^* + (\Delta\text{Peak}^{\text{abs}})_{i,c}^* + (\Delta\text{Distance}^{\text{abs}})_{i,c}^* + (\Delta\text{Width}^{\text{abs}})_{i,c}^* \quad (5)$$

Based on this definition, the TNI value for each station and period ranged from 0 to 6. The average calculation only changed the scale without affecting the ranking results, spatial patterns, or clustering. Therefore, TNI interpretation remained comparative within each dataset and period, which was supported by all metrics.

Min-max normalization had limitations due to its sensitivity to extreme values, necessitating comparative TNI interpretation within a given dataset and decade. Z-scores or other scaling methods were not applied in this study and were recommended for future analysis (Mazziotta and Pareto, 2022).

2.6 Significance assessment

Statistical significance was assessed by calculating nonparametric bootstrap confidence intervals (CIs) for the metric at each station and decade (Efron and Tibshirani, 1994). Only station-decade data with at least 90% of the months (≥ 108 months) were used for resampling, and all metrics were recalculated at each bootstrap replicate.

Percentile CIs were calculated at the 95%, 90%, and 75% confidence levels ($\alpha=5\%$, 10% , and 25%). A change was considered significant when the confidence interval did not include zero, namely for WD and KL. The lower bound of the CI must be greater than 0. For OVL, the upper bound of the CI must be less than 1. In the case of ΔPeak , $\Delta\text{Distance}$, and ΔWidth , the CI must not contain 0. The final inference method used this bootstrap-based criterion without the additional use of the Wilcoxon signed-rank test, as the analysis focused on the distribution function, and uncertainty was already captured by the bootstrap method. In the visualization, the significance levels $\alpha = 5\%$, 10% , and 25% were marked with the symbols X, Y, and Z, respectively.

2.7 Spatial clustering

K-means clustering was used on station TNI values to establish spatially coherent groups that share common characteristics of change. The elbow, silhouette, and Davies-Bouldin criteria methods were used to pick the number of clusters (Rahman et al., 2024; Pratama and Salam, 2025). K-means was selected because it was a centroid-based partitioning algorithm that was relatively easy to implement and computationally inexpensive. The method could also be readily understood through centroid representation and minimization of within-cluster sum of squares (Ikotun et al., 2023; Wani, 2024). An example of a very brief sensitivity analysis using close-to-neighbour K values showed the same most pronounced west-central-east pattern. However, alternative clustering algorithms were not evaluated (Roux et al., 2021).

3. RESULTS AND DISCUSSION

Understanding the evolution of decadal rainfall requires not only determining changes in totals but also examining how the shape, intensity, timing, and variability of rainfall distributions vary over time. In this section, six distribution-based measures and a bootstrap significance test ($\alpha=5\%$, 10% , 25%) are used to analyze the spatial distribution of rainfall transformation in the North Coast of Central Java, using both the Observation and CHIRPS data. The results of the study were categorized into two major groups. The first group consisted of shape-based metrics, including displacement, divergence, and overlap of distribution (WD, KL, and OVL). Meanwhile, the second group comprised morphology-based metrics, which compare changes in the peak, centroid, and width of the distribution (ΔPeak , $\Delta\text{Distance}$, ΔWidth). These six measures were

integrated into a TNI and then spatially analyzed to extract major areas where a change in the distribution of rainfall is taking place.

In order to promote comprehension, every metric was only described once and applied throughout the results. These included WD, KL, OVL, and ΔPeak , $\Delta\text{Distance}$, and ΔWidth (morphology measures). Changes between decades will be denoted as change a between 2001-2010 and 1991-2000, as well as change b between 2011-2020 and 2001-2010.

3.1 Shape-based distribution metrics

Figure 3 shows the spatial distribution of three shape-based measures of observations (A1-C1) and CHIRPS (A2-C2). All these measures together show the changes in the distribution and structure of rainfall over decades.

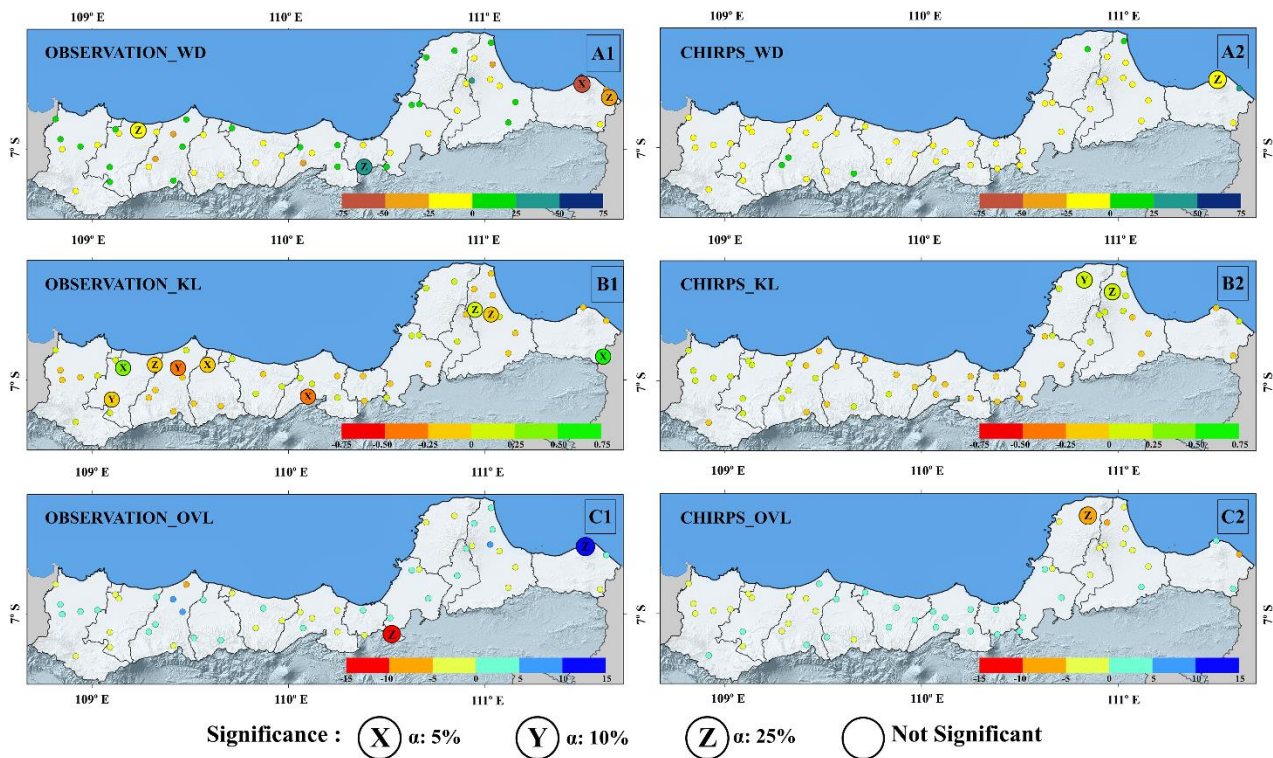


Figure 3. Shape-based rainfall measures (WD, KL, OVL) of observations (A1-C1) and CHIRPS (A2-C2) with significant levels, X (5%), Y (10%), and Z (25%).

The WD showed that the western and eastern areas exhibited a significant difference in terms of movement of rainfall, with the western corridor registering a greater change. These results suggested that there were alterations in the intensity of rainfall and dramatic structural changes in the western area over the past decade. CHIRPS data exhibited the same

trend, but the shift appeared smoother, reflecting the spatial smoothing inherent in gridded data.

KL showed a nonlinear change in the shape of the distribution, specifically in the central and eastern areas. Higher values of KL in observations suggested that there was greater variability in rainfall. CHIRPS captured the broader gradient while underestimating localized differences. The OVL was built upon the last

result by identifying the areas where distribution has grown dissimilar over decades. The western and northeast areas of the coastlines had a lower value of OVL, which showed a high level of structural variation. The central area had a greater value, suggesting relative stability. Evaluation of all three measures showed that significant markers of change (X, Y, Z) established the presence of distributional changes at several stations. Observational data showed

more localized changes, while CHIRPS data had greater areal consistency.

3.2 Morphology-based metrics

The morphology-based statistics of Observations (A1-C1) and CHIRPS (A2-C2) (Figure 4) showed the changes in the rainfall intensity, central tendency, and seasonal variability during the decades.

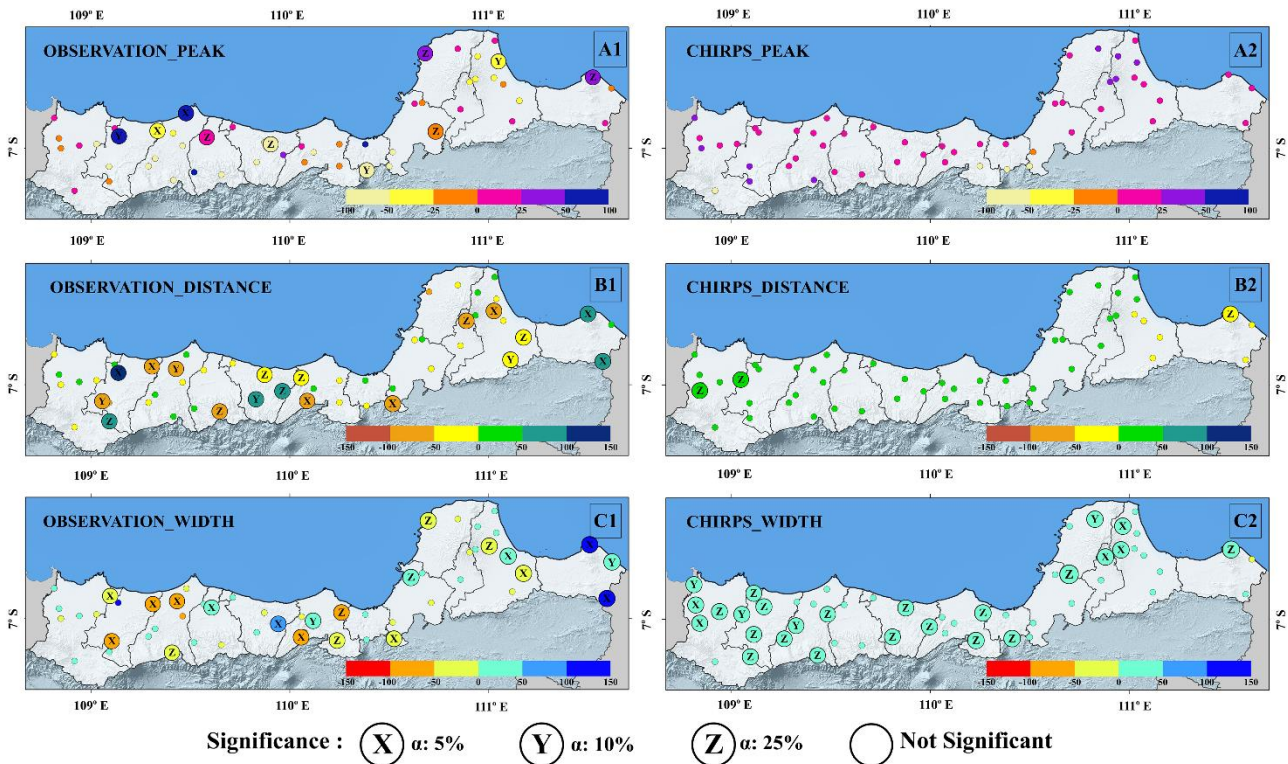


Figure 4. Morphology-based rainfall metrics (Δ Peak, Δ Distance, Δ Width) for observations (A1-C1) and CHIRPS (A2-C2), with significance markers X (5%), Y (10%), and Z (25%).

The Δ Peak represented the growth in rainfall intensity in the western and northeastern range, with positive values denoting heavier rainfall in the last decades. A significant portion of the eastern areas had smaller peak intensities, showing varied rainfall-intensification patterns throughout the area. CHIRPS could capture the general trends, but only a few important stations.

Δ Distance represented the separation between the centroid of the distribution, showing significant movement in the western and eastern areas. This observation showed the tendency of rainfall rearrangement, and could be moving either way in terms of intensities, to the heavy or light end, based on the area. Observation data contained more detailed spatial features, while CHIRPS data showed more gradual decadal variations.

Δ Width showed the opposite rainfall variability regimes. Western Pantura exhibited negative Δ Width predominantly, process distribution was narrow, and rainfall events were concentrated. Eastern Pantura exhibited a positive change in Δ Width, suggesting that intra-annual variability was greater and the rainfall pattern was more dispersed. These identified spatial contrasts were also consistent across datasets, but CHIRPS contained more generalized gradients.

The Δ Peak- Δ Distance- Δ Width measured all points to a consistent morphological change. An intensification and westward concentration tendency occurred, accompanied by expansion in the eastern region. Statistical significance further confirmed the strength of these changes.

3.3 Transformation of the TNI

The 6 measures were summed to obtain the TNI, a unified, holistic measure of the changes in the rainfall distribution. Figure 5 shows the patterns of TNI of observations and CHIRPS, and Table 2 contains the bootstrap value of significance.

Figure 6 provided a station-wise comparison between observation-based and CHIRPS-based TNI for each decadal transition, using an identity line to

visualize agreement and systematic bias. The western and eastern areas exhibited high TNI values (0-6), representing more substantial structural alterations. Meanwhile, the central area showed moderate TNI values, consistent with transitional rainfall patterns. All transitions in Figure 5 (a)-(d) showed a statistically significant shift (lower CI>0), suggesting that the transformation of rainfall in Pantura was both systematic and meaningful.

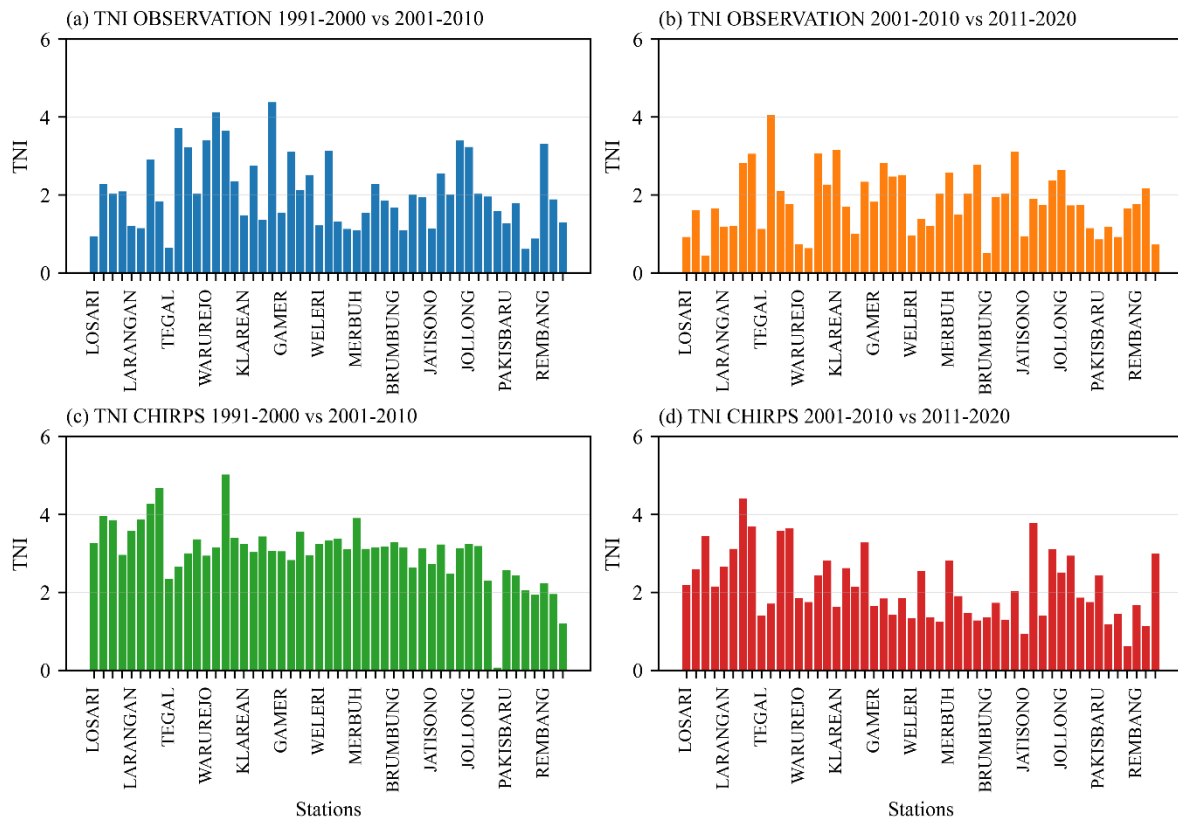


Figure 5. Spatial pattern of TNI in stations ranked by longitude (west to east) in two decadal comparisons (a-b) observations and (c-d) CHIRPS.

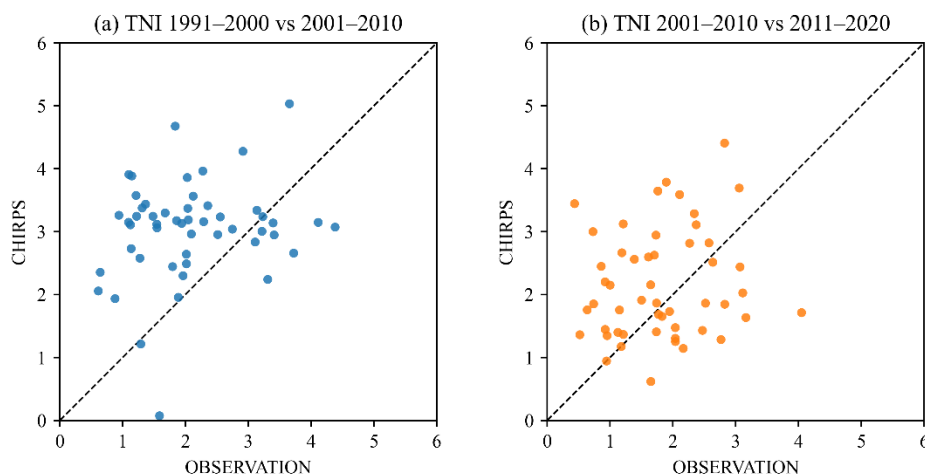


Figure 6. Station-wise relationship between observation-based TNI and CHIRPS-based TNI for the two decadal transitions. The dashed line denotes the identity line. (a) 2001-2010 vs 1991-2000; (b) 2011-2020 vs 2001-2010.

Table 2. Mean total normalized index (TNI; unitless, range 0-6) and bootstrap confidence intervals (BCIs) for two adjacent-decade comparisons. BCIs are reported as lower-upper bounds; significance flags show whether the CI excludes the null.

Dataset and decadal comparison	Mean TNI	BCI 95% (lower-upper)	Sig. ($\alpha=0.05$)	BCI 90% (lower-upper)	Sig. ($\alpha=0.10$)	BCI 75% (lower-upper)	Sig. ($\alpha=0.25$)
Observation (2001-2010 vs 1991-2000)	2.081	1.823-2.339	Yes	1.874-2.288	Yes	1.933-2.229	Yes
Observation (2011-2020 vs 2001-2010)	1.804	1.588-2.020	Yes	1.618-1.990	Yes	1.674-1.934	Yes
CHIRPS (2001-2010 vs 1991-2000)	3.038	2.829-3.247	Yes	2.859-3.217	Yes	2.914-3.162	Yes
CHIRPS (2011-2020 vs 2001-2010)	2.160	1.921-2.399	Yes	1.968-2.352	Yes	2.023-2.297	Yes

CHIRPS tended to produce larger TNI values because of its less abrupt transitions over decades, while the spatial gradients of CHIRPS were similar to those of observations. As shown in Figure 6, the X-Y relationship plot suggested that CHIRPS generally followed the transformation signal obtained at the station during both transitions, although the points tended to be above the identity line. This result suggested that the CHIRPS-based TNI was higher systematically but was otherwise consistent with the general trend of the gradient.

3.4 Spatial clustering of rainfall distribution shift

K-means clustering integrated the six distributional measures into consistent spatial clusters, which showed major trends of decadal rainfall change. Combining validation indices (Silhouette, Davies-Bouldin and Calinski-Harabasz), the number of clusters to be used during each transition period was selected automatically (Tables 3-4). The results showed that there were significant differences between Observations and CHIRPS regarding spatial heterogeneity.

Table 3. Observation K-means clustering 2001-2010 vs 1991-2000 and 2011-2020 vs 2001-2010

2001-2010 vs 1991-2000		2011-2020 vs 2001-2010	
Cluster	Regency	Cluster	Regency
0	Brebes, Pekalongan, Pemalang, Tegal	0	Demak, Kendal, Semarang
1	Demak, Kudus, Pati, Rembang	1	Jepara, Kudus, Pati
2	Batang, Kendal, Pekalongan, Pemalang, Tegal	2	Batang, Demak, Kendal, Pekalongan, Semarang
3	Kudus, Pati, Rembang	3	Brebes, Pekalongan, Pemalang
4	Batang, Demak, Kendal, Semarang	4	Pemalang, Tegal
5	Brebes, Pekalongan, Pemalang, Tegal	5	Jepara, Pati, Rembang
6	Jepara, Pati	6	Brebes, Pekalongan, Pemalang, Tegal
		7	Pati, Rembang
		8	Demak, Kudus, Pati, Rembang
		9	Pemalang, Tegal

Table 4. CHIRPS K-means clustering 2001-2010 vs 1991-2000 and 2011-2020 vs 2001-2010

2001-2010 vs 1991-2000		2011-2020 vs 2001-2010	
Cluster	Regency	Cluster	Regency
0	Demak, Kudus	0	Brebes, Kendal, Pekalongan, Pemalang
1	Brebes, Pekalongan, Pemalang	1	Jepara, Pati, Rembang
2	Pati	2	Demak, Kudus, Pati, Rembang
3	Pekalongan, Pemalang, Tegal	3	Brebes, Pemalang
4	Batang, Demak, Kendal, Semarang	4	Batang, Demak, Kendal, Semarang
5	Pati, Rembang	5	Pekalongan, Pemalang, Tegal
6	Pemalang, Tegal	6	Brebes, Pekalongan, Pemalang, Tegal
7	Pati, Rembang	7	Jepara, Kudus, Pati, Rembang
8	Brebes		
9	Jepara, Kudus, Pati		

3.4.1 Based on observational data

Clustering of observations (Figure 7) showed a high level of spatial fragmentation, suggesting that microclimatic and topographic factors exerted a significant impact on the variation of rainfall in the North Coast. Within the first transition period (1991-2000 to 2001-2010), clusters were mostly found along the western central corridor. Consequently, early decadal variability was localized in areas where there was a strong convective velocity and strong land-sea interaction.

In the second transition (2001-2010 to 2011-2020), the cluster arrangement was reorganized seriously to the north-east direction with the precipitation transformation shift to the east. This change was consistent with the increasing influence of sea surface temperature anomalies in the Java Sea and enhanced convective activity in the eastern area during the past decade. The observation clusters were also finer compared to CHIRPS, capturing the fine-scale variations caused by local rainfall characteristics in certain stations.

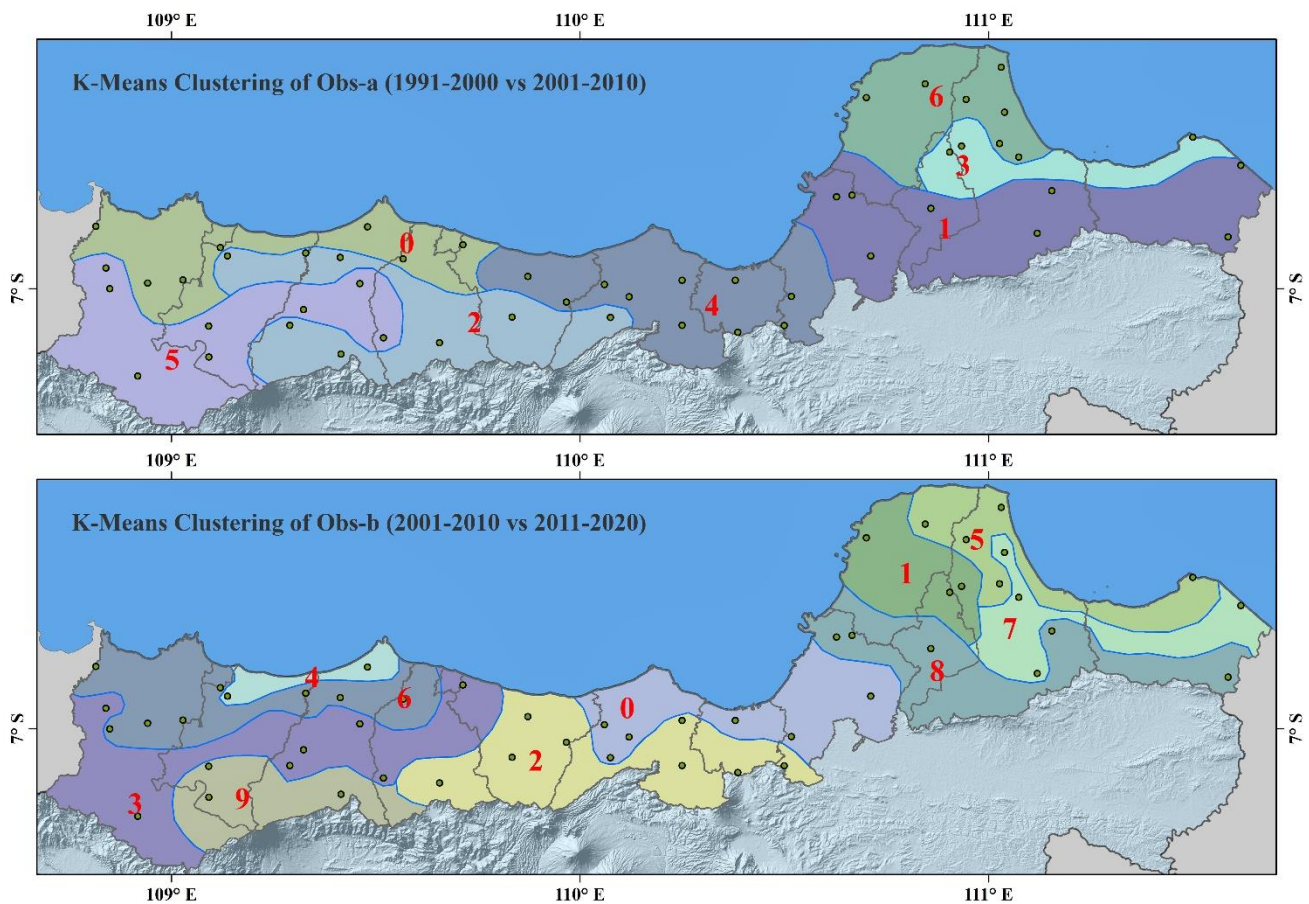


Figure 7. Two periods of transition (Obs-a and Obs-b) between observational data and the clustering of rainfall distribution using K-means. The clusters are the spatial areas that have a similar decadal variation of rainfall based on the six distribution measures.

3.4.2 Based on CHIRPS data

Figure 8 provides an even more coherent space zone in the regional clustering of CHIRPS data. The western and central areas were variable, accumulating in the early period of transition, and the eastern area was rather steady. The second transition period saw a change in the pattern of clustering to the east and showed a high variation in the area of Demak-Kudus-Jepara-Pati-Rembang. This easterly trend was consistent with the tendencies of observation, but

CHIRPS had fewer definite frontiers, focusing more on regional influences rather than the local ones.

In both transitions, CHIRPS provided 3 wide regional shift, namely (1) Western intensification, (2) Central transitional corridor, and (3) Eastern variability expansion. These areas were consistent with the spatial changes conveyed by the six distributional metrics, particularly ΔPeak , $\Delta\text{Distance}$, and ΔWidth .

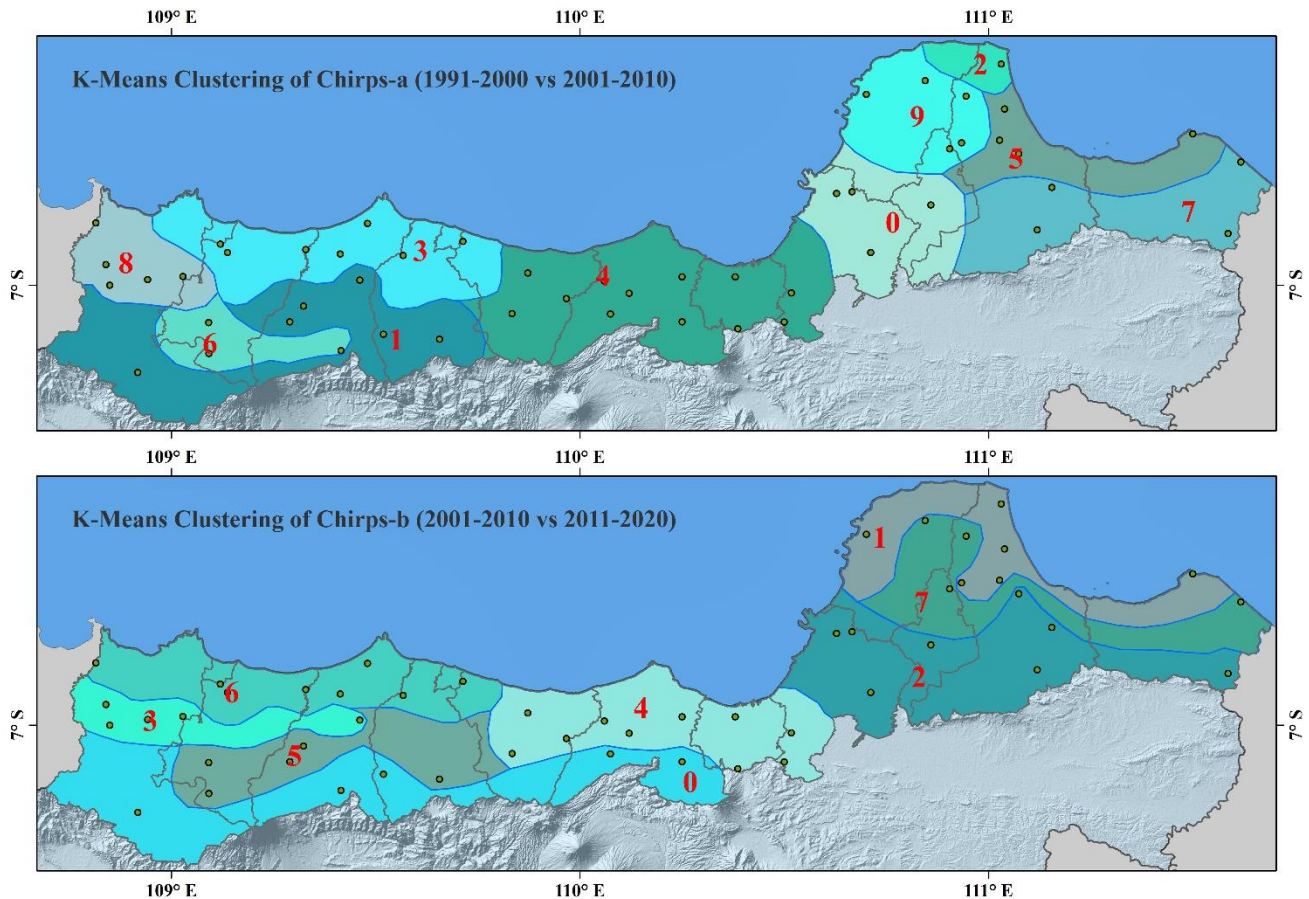


Figure 8. K-means clustering of the rainfall distribution between CHIRPS data between two transition periods (Chirps-a and Chirps-b). The clusters show regionally consistent patterns of rainfall change and emphasize the occurrence of consistent trends of west-east gradients over decades.

3.4.3 Consistency between observations and CHIRPS

Figure 6 assessed the consistency by comparing the TNI values of observational (TNI_Obs) and CHIRPS (TNI_CHIRPS) data on each of the transition periods with the identity line as the reference. In general, the transformation pattern at the station was reproduced by CHIRPS. It provided a greater range of values, showing that there were differences in the representation of the observational and grid data, and the fluctuations around the identity line.

The similarity in the eastward movement of the variability signal in both datasets and the identified transition period showed that the past ten years were characterized by active modification of precipitation patterns in the northeastern coastal area. These results showed the joint influence of monsoonal circulation, trends of changing conditions of the surface in the Java Sea and the intricate coastline topography in the area.

The clustering results collectively provided a comprehensive view of how rainfall transformation occurs in the North Coast. Furthermore, the

complementary results from Observations and CHIRPS, local sensitivity and regional coherence, provided a strong foundation for interpreting long-term climate trends and supporting planning to anticipate the impacts of hydrometeorological disasters on the coast of Central Java.

3.5 Mechanistic interpretation and literature comparison

The focus of this section was on the interpretation of changes in rainfall distribution on a decadal scale by comparing ten-year periods (1991-2000, 2001-2010, 2011-2020) to show interannual variability and also long-term climate evolution. Therefore, ENSO and IOD were viewed only as interannual modulators that alter annual variations or seasonal extreme events, not as causes of decadal rainfall changes as shown in this study. To date, there have been limited studies on histogram-based distribution diagnosis methods and composite indices. However, the decadal pattern changes observed were consistent with other studies that used trend analysis,

rainfall indices, or extreme indices, as well as with the presence of multidecadal changes in tropical coastal areas affected by the monsoon. The result of this present study showed a transformation of moderate to strong rainfall at the station level, as evidenced by the TNI values. These values were derived from observational data (average TNI around 1.8-2.1) and CHIRPS data (around 2.2-3.0), on a scale range of 0-6 over the two decades compared (Table 2).

Similar patterns of changes in rainfall distribution have been reported in several other areas. These included patterns found in a study on seasonal changes in the watershed of the Panama Canal (Hatvani et al., 2025) and shift in distribution in the coastal area of Victoria, Australia (Tolhurst et al., 2023). Although the metric and scopes used vary, these changes appeared to form a distinct regional gradient rather than an average change. These results showed the need to know more about the distribution patterns to determine the real processes of climate change taking place in the area.

In Indonesia, rainfall was very diverse, with the monsoon system influencing the southern area of Java. Similarly, the monsoon influenced the northern region of Central Java (Pantura), with its effects shaped by changes in circulation and sea surface temperature both regionally and globally. This result initiated alterations in the distribution of rainfall that were sensitive to changing regional circulation patterns and sea surface temperatures (Aldrian and Susanto, 2003).

In most instances, the coastal areas, such as the Pantura, enjoyed heavy rainfall along the coastline, and this happened daily due to the interplay of sea and land breezes. This natural process established a space gradient, and the rain pattern in Pantura was different and distinct compared to other areas (Yamanaka, 2016).

ENSO and IOD had a very strong effect on year-to-year changes in rainfall in Indonesia (particularly during the JJA-SON), which grew stronger during SON (Nur'utami and Hidayat, 2016; Supari et al., 2018). The west-central-east pattern uncovered in the rainfall distribution of Pantura showed that day-to-day coastal processes and the monsoon background were the primary forces that influenced the formation of a structured spatial gradient, such as the peak, centroid and width measures. ENSO and IOD continued to regulate annual rainfall variation during certain seasons, making the annual patterns in Indonesia highly dynamic (Kurniadi et al., 2021).

ENSO and IOD provided a reasonable foundation for understanding rainfall variations in Indonesia, and the monsoon circulation was suspected to influence how these two phenomena affect coastal rainfall. This study did not conduct direct attribution analysis using statistical methods, such as correlation or composite indices (Niño 3.4 and DMI), or diagnostics using monsoon indices. Decadal variations and interannual variability were not also divided effectively. In future studies, Additional studies were needed using more detailed methodologies, such as seasonal correlation, composite analysis, or stratification, to better connect rainfall distribution measurements with ENSO, IOD, or monsoon dynamics.

4. CONCLUSION

In conclusion, this study calculates decadal shift in the monthly rainfall distribution using smoothed histograms, six measures of distribution, and the aggregate TNI. The aim is to compare the changes in monthly rainfall distribution in the Pantura (North Coast) of Central Java in terms of 51 BMKG stations and CHIRPS v2.0 (1991-2020). The major results show a distinct west-central-east gradient, with concentration increasing in the west, moderate restructuring in the central area, and a wider distribution with higher variability in the eastern area over the past decade. The CHIRPS data summarizes regional trends but has a tendency to blur out local trends as opposed to observed data.

Changes in the distribution of rainfall should be taken into account when dealing with coastal risk management. The areas where the rainfall concentration is rising should enhance drainage and flood prevention. Furthermore, the mitigation planning should consider peak intensity and variability in order to cope with short and wet months with a lot of rainfall. Increased variability also demands greater flexibility in preparedness plans, including adjustments to planting schedules and drought management. The constant control with the help of rain gauges and satellite data is essential to keep risk maps up to date and prioritize interventions.

A key limitation of this study is that it did not formally attribute change to particular drivers of climate. There is also no explicit distinction between low-frequency (decadal) change and interannual variability, such as ENSO or IOD. Future studies need to measure the connection with Niño 3.4 or DMI

correlation-composites and add monsoon indices as an important background circulation comparator.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Validation, Formal analysis, Resources, Data Curation, Visualization, Funding acquisition, and Writing-Original Draft Preparation, Iis Widya Harmoko; Supervision, Writing-Review and Editing, Muhammad Zainuri, Anindya Wirasatriya, and Supari; Software, Formal analysis, Investigation, Aviv Maghridlo.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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Sustainable Valorization of Domestic Onion Waste: Comprehensive Characterization for Nutrient Recovery and Waste Volume Reduction

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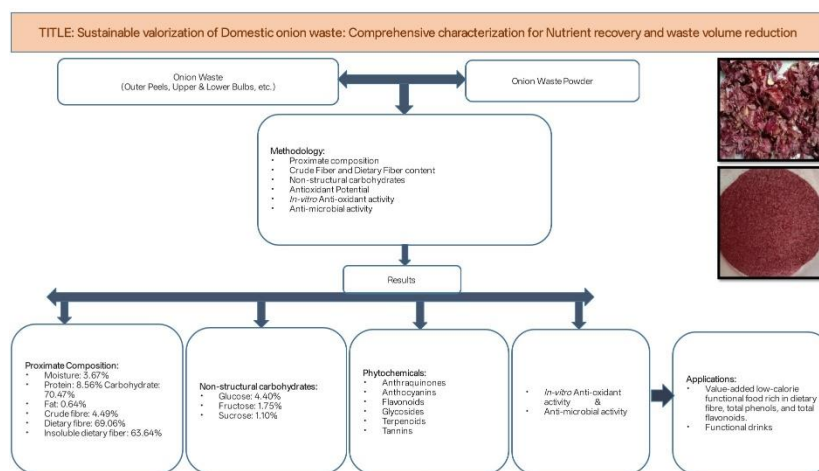
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GRAPHICAL ABSTRACT



ABSTRACT

Allium cepa L., commonly known as onion, is one of the most widely cultivated vegetables worldwide, valued for its characteristic flavor, aroma, and pungency. It is extremely concerning that around one million tonne of onion waste is produced throughout distribution, processing, and consumption. Characterization of onion waste is essential for its valorization. The study's goal was to identify the nutritional and nonstructural carbohydrate content, antioxidant, antimicrobial activity and phytochemical elements present in the waste. The onion waste was cleaned and dried at 60°C in an air-circulating tray dryer, and ground into a fine powder. It was found to contain moisture (3.67%), protein (8.56%), carbohydrate (70.47%), fat (0.64%), crude fibre (4.49%), dietary fibre (69.06%), and insoluble dietary fibre (63.64%) and provides 321.88 kcal of energy per 100 g. The non-structural carbohydrates in the onion waste were glucose (4.40%), fructose (1.75%) and sucrose (1.10%). The ethanolic onion waste extract was found to contain phytochemicals anthraquinones, anthocyanins, phenols, flavonoids, glycosides, terpenoids, flavonoids, and tannins. Using DPPH and hydroxyl radical scavenging activity, the antioxidant activity of ethanolic onion waste extract was revealed to be strong at various concentrations. These values ranged from 42.34% to 70.50%, 65.8 to 60.5%, respectively. The ethanol extract of onion waste was found to have the strongest anti-microbial effects on *Escherichia coli* and *Staphylococcus aureus*. Onion waste characterization provides valuable insights into its potential as a source of bioactive compounds facilitating its utilization in nutraceuticals and functional foods. This approach promotes sustainable waste management and resource utilization while unlocking the hidden potential of onion waste.

HIGHLIGHTS

The study explores characterization as well as functional potential of onion waste. The onion waste powder was found to be rich in dietary fibre. It is a good source of phytochemicals. Onion waste also possesses strong antioxidant and antimicrobial activities.

1. INTRODUCTION

Onion (*Allium cepa* L.) is considered as Queen of Kitchen, a commonly used crop that incorporates in

the daily diet for most of the regions and is economically important all over the world. It is also consumed as basic ingredient for preparation of salad,

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stews, and soups and as a cooked vegetable for major population (Gupta et al., 2025). Industrial processing of onion includes production of onion flakes, powder, oil and pickle. The global production of onion is around 105 million tonnes (MT) with China, India, Egypt, United States of America and Iran as the five major contributors. India is the second largest onion producing country in the world after China. The production of onion in the year 2025 is estimated around 31.7 million tonnes which is around 25% of the global onion production (World Population Review, 2025). Onions are mainly grown in temperate regions and are categorized based on colour and pungency. The round shaped onions are widely grown and are red, white and yellow coloured (Britannica, 2025).

Apart from the taste, onion also provides health benefits to its consumer. Traditionally, onion has been used as medicine in Asia due to its various health benefits. It acts as stimulant and has therapeutic characteristics since centuries for the treatment of cold, cough, bronchitis, and influenza. It also safeguards the human body from cancer, fungal and bacterial infection, reduces blood pressure, decreases thickening of blood, lowers heart stroke and overall reduces the cardiovascular diseases (Singh and Khar, 2022; Jain et al., 2019).

There is huge demand of onions worldwide. As onions are so commonly consumed, the volume of domestic onion waste is much greater than that of industrial onion waste and its environmental impact is significantly higher. Globally, around 1MT of onion waste is generated (Jaganmohanrao, 2025). When the onion waste decomposes in the environment and is combined with soil, it also leads to nutrient degradation through spread of post-harvest fungi, which in turn has an impact on the atmosphere. When raw onion waste with high sulphur content and rapidly fermentable organic matter is added to soil, soil microbes break down sulphur-containing compounds, producing sulphate and H^+ ions that lower soil pH, which can change nutrient solubility and lead to nutrient imbalances, temporarily shifting the soil microbial community, sulphur oxidation and reducing the availability of other nutrients like nitrogen or phosphorus due to changed microbial competition and nutrient transformations, resulting in nutrient degradation in the soil (Liang et al., 2025). Due to its potent flavour of sulphur compounds and taste, onion waste is not ideal for use as high concentrations of feed, and it cannot be used as inorganic fertilizer since it serves as a substrate for the phylogenetic agents'

quickest growth (Chorolque et al., 2022). The method and procedure for using it need to be developed. The wastes are made up of onion outer skin, bulbs, outer fleshy scales, roots, peels, damaged, infected and undersized bulbs, etc. They are categorized in three different categories: industrial waste, domestic waste and supply chain or distribution waste. The onion waste amounts to around 38% of the fresh onion weight and about 10% of onions are wasted as distribution losses (El Mashad et al., 2019). Domestic onion waste amounts to around 20% of the total onion production in India (Bose, 2025). Onion waste is a rich source of bioactive compounds such as phenols, flavonoids and flavanols. The flavonoid content of the onion waste is up to 10 g/kg more than the flavonoids content in the edible part of the onion (Akdeniz et al., 2018). The presence of these bioactive compounds gives the medicinal properties useful in prevention of neurodegenerative disorders, diabetes, cancer, cardiovascular diseases, microbial infections, and erectile dysfunction (Kumar et al., 2022b).

The onion waste is capable of producing a variety of useful substances, including bioactive compounds e.g., phytochemicals, dietary fibre, and proteins, as well as other products such as bio-colorants, edible oils, enzymes, organic acids, activated carbon, degradable plastic composites, cosmetics, bio-sorbent, resins, medicines, foods and feeds, methane, biopesticides, etc. (Zahid and Khedkar, 2022; Zahid et al., 2025; Thakur and Modi, 2024). Shahid et al. (2023) examined production of bioethanol from onion waste with co-culture fermentation using *Saccharomyces cerevisiae* and *Pichia pastoris*. Bioethanol concentration of 22.72 g/L with energy 681.6 kJ/L was produced with the coculture fermentation at 30°C for 86 h at pH 5. The presence of reducing sugars helped in greater yield of bioethanol from monoculture fermentation using *Saccharomyces cerevisiae*. The onion wastes are nutrient-rich and can also serve as a substrate for the production of industrial amino acids, single cell proteins, essential oils, and exogenous enzymes, all of which lead to products with added value. Similarly, the management for food industry waste is the demanding concern of consumer to protect the environment (Khedkar and Singh, 2017).

The dry matter in onion is mainly composed of (around 80%) non-structural carbohydrates in the form of fructo-oligosaccharides (FOS), sucrose and reducing sugars e.g. glucose and fructose that make up the majority of the dietary reserves and energy

source taking part in the growth and metabolism of onions (Aisara et al., 2021). FOS are the sugar substitutes that have no calories and are not carcinogenic, which helps to boost immune system performance and gastrointestinal physiology and are used in the bakery, dairy and confectionery industry (Kherade et al., 2021).

In order to make use of onion waste, the present endeavour was conducted to investigate the nutritional content, phytochemical composition, non-structural carbohydrates composition, antioxidant, and antimicrobial activity. The study helped in evaluating the functional potential of onion waste for sustainable resource utilization.

2. METHODOLOGY

2.1 Materials

The red onion waste (Pusa Red variety) was procured from a local market in Jasola Vihar, Delhi, India, 110025 and the chemicals used for the analytical purpose were purchased from Sigma-Aldrich, India.

2.2 Sample preparation

The red onion waste was washed with distilled water two to three times in order to remove all the dirt and dust adhering to the waste. Thereafter, the waste was dried in a tray drier (Bionics Instruments, India) at $60 \pm 2^\circ\text{C}$ by placing a fine layer of waste material on individual tray for uniform drying of the material till constant weight was achieved. The sample was then ground into fine powder by using an automatic grinding machine (Maharaja Whiteline Mixer Grinder, India) and was sieved through BS30 (500 microns) sieve. For subsequent investigation, the powdered material was kept in an airtight container and refrigerated at 4°C . Figure 1 represents the powdered onion waste sample that was used for further analysis.

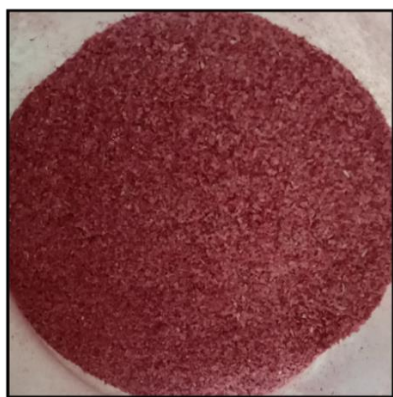


Figure 1. Onion waste powder

2.3 Determination of proximate composition of onion waste

The proximate composition, including moisture, crude protein, ash, crude fat, carbohydrate and energy content was analysed following the standard procedures described by (AOAC, 2023; AACC, 2025).

2.3.1 Determination of moisture content

The moisture content of powdered onion wastes sample was determined by the standard hot air oven method (AACC, 2025). Around 10 g of sample was heated in hot air oven (Labindia Instruments, India) at a temperature of $110 \pm 2^\circ\text{C}$ until the constant weight was achieved. The moisture content of the onion sample was obtained as follows:

$$\text{Moisture (\%)} = \left[\frac{(\text{Wt. of original sample} - \text{Wt. of dried sample})}{\text{Wt. of original sample}} \right] \times 100$$

2.3.2 Determination of crude protein content (Kjeldahl Method)

The crude protein of powdered onion sample was estimated by Kjeldahl Method which includes protein digestion using conc. H_2SO_4 , distillation with 40% NaOH and titration with 0.116 N HCl in a Kjeldahl (Techno reach, India) apparatus (AOAC, 2023).

%Nitrogen was calculated by using the formula:

$$\% \text{Nitrogen} = (V_s - V_B) \times M_{\text{acid}} \times 0.01401 \times 100 W$$

Where; V_s =volume (mL) of acid required to titrate sample; V_B =volume (mL) of acid required to titrate the blank; M_{acid} =molarity of acid; W =weight of sample (g). Then, percentage crude protein in the sample was calculated from the % Nitrogen as % crude protein = $\%N \times F$, where, F (conversion factor), is equivalent to 6.25.

2.3.3 Determination of ash content

Ash content is the inorganic residue obtained by the complete burning of material. About 5-10 g sample was weighed in a tared crucible. Crucible was placed in muffle furnace (Bionics Scientific, India) and heated at $525-550^\circ\text{C}$ for 6 hrs, until the ash was obtained. The crucible containing ash was allowed to cool in a desiccator and then reweighed (AOAC, 2023). The % ash content was calculated by the following:

$$\text{Ash (\%)} = \frac{\text{Wt. of ash}}{\text{Wt. of sample taken}} \times 100$$

2.3.4 Determination of crude fat content

The crude fat content of onion waste sample was determined by Soxhlet (Bionics Scientific, India) extraction method (AOAC, 2023). About 3.0 g of moisture free sample was weighed and transferred to a thimble. The thimble was placed in the Soxhlet apparatus. Around 75 mL petroleum ether was poured through the sample in the flask and allowed to reflux for 24 hrs. The thimble was removed and petroleum ether was recovered for re-use. The flask was subjected to heat at $100 \pm 2^\circ\text{C}$ until it was free from petroleum ether. After drying it was cooled in a desiccator and weighed (AACC, 2025). The % crude fat was estimated by the following:

$$\text{Crude Fat (\%)} = \frac{\text{Wt. of fat}}{\text{Wt. of original sample}} \times 100$$

2.3.5 Determination of total carbohydrate

The total carbohydrate content of onion waste sample was determined by the difference method (Khedkar et al., 2023).

$$\% \text{ Carbohydrate} = 100 - (\% \text{ moisture} + \% \text{ crude fibre} + \% \text{ protein} + \% \text{ lipid} + \% \text{ ash})$$

2.3.6 Determination of energy value of onion samples

The energy value of the samples was determined by multiplying the protein content by 4, carbohydrate content by 4 and fat content by 9 (AOAC, 2023).

$$\text{Energy value} = (\text{Crude Protein} \times 4) + (\text{Total carbohydrate} \times 4) + \text{Crude fat} \times 9$$

2.3.7 Determination of crude fibre and dietary fibre content

The crude fibre content of the sample was obtained using the procedure described in AOAC (2023). Around 2 g of defatted powdered onion waste was taken into a flask and 100 mL of 0.255 N H_2SO_4 was added for the acid wash. The mixture was then heated under reflux with heating mantle at $400 \pm 5^\circ\text{C}$ for one hour. Subsequently, alkali wash was done with 100 mL of 0.313 M NaOH. The mixture was filtered through a fibre sieve cloth, after which 10 mL of acetone was added to dissolve the remaining organic constituents. The residue was washed twice with 50

mL of hot water and then transferred into a pre-weighed crucible. The crucible containing the residue was oven-dried at $110 \pm 2^\circ\text{C}$ overnight to remove residual moisture, cooled and weighed (W1), after which it was subjected to ashing at $525\text{--}550^\circ\text{C}$ for 4 hrs in a muffle furnace. The crucible containing the white and grey ash, free of carbonaceous material, was cooled in a desiccator and weighed to obtain (W2). The % Crude Fibre content was estimated by the following:

$$\text{Crude Fibre(\%)} = \left(\frac{W1 - W2}{\text{Wt. of sample}} \right) \times 100$$

The total dietary fibre (TDF), soluble dietary fibre (SDF), and insoluble dietary fibre (IDF) contents of the powder were determined by the enzymatic-gravimetric method, using the Bioquant 1.12979.0001 total dietary fibre assay kit (Merck, Germany).

2.4 Determination of non-structural carbohydrates of onion waste

The sugar content of powdered onion wastes sample was estimated by High Performance Liquid Chromatography (Shimadzu LC-2010HT with RI detector) as per the standard procedure mentioned in AOAC (2023). The HPLC column was Luna 5 μm NH_2 100Å LC column (250×4.6 mm). The standard sugar solution was made by combining 3.804 g of fructose, 3.010 g of glucose, and 0.602 g of sucrose in a 100 mL volumetric flask, dissolving them in 50 mL of water, and then adding CH_3CN to volume to create the mobile phase. Under operating conditions of flow rate of approximately 1.0 mL/min, ambient temperature of approximately 23°C , detector was set so that 380 g fructose gives full scale peak and mono, di, and tri-saccharides are eluted from column under the influence of molecular weight, fructose, glucose, and sucrose are separated and quantified in 20 min. To create the test sample, 5 g of onion waste powder was weighed in a tiny beaker and transferred to a 50 mL volumetric flask with 25 mL of water. Then, using a clarity kit, it was promptly diluted to volume with CH_3CN and filtered through a 0.45- μm filter. 10 μL of standard solution was injected into chromatograph. The retention time were established; peak height and reproducibility were measured. The whole procedure was repeated for onion waste sample. The glucose, fructose, and sucrose from integrator values or from peak heights were calculated by the formula given below:

$$\text{Weight percent sugar} = 100 \times \frac{P_0}{P} \times \frac{V_0}{V} \times \frac{W}{W_0}$$

Where; P_0 and P is peak heights (or integrator values) of onion waste solution and standard, respectively; V_0 and V is onion waste solution and standard (50 and 100 in mL) solution, respectively; W_0 and W is g onion waste sample (5 g) and standard, respectively.

2.5 Phytochemical screening and antioxidant potential of onion waste

2.5.1 Preparation of extract

The onion waste extract was prepared by mixing 50 g of powdered sample with 250 mL of ethanol (95%) and incubating the suspension overnight at room temperature under shaking conditions. Extraction was conducted until the extraction solvent was colourless. The extracts obtained after each extraction cycle were pooled and filtered using Whatman filter paper no. 1 and finally concentrated for 25 min on a rotary vacuum evaporator (Hahn Shin Scientific, India) with a vacuum of 562 mmHg, temperature 40°C, and 200 rpm. The concentrated extract was stored at 4°C to stop oxidation and for further use. Similarly, the methanol and hexane extracts of the onion waste powder were also prepared.

2.5.2 Qualitative determination of phytochemical screening

The ethanolic extracts of onion waste were subjected to qualitative phytochemical screening. The methods used were Molisch's, Fehling's, alkaloid, foaming, ferric chloride (FeCl_3), alkali, Borntrager's, and Keller-Killani tests for qualitative determination of anthraquinones, anthocyanins, flavonoids, glycosides, terpenoids, flavonoids, and tannins respectively (Singh et al., 2022; Sayeed et al., 2020).

2.5.3 Determination of total phenolic content (TPC)

Phenols are secondary plant metabolites that serve as defence chemicals. The total phenolic content in ethanolic, methanolic, and hexane onion waste extract were estimated by Folin-Ciocalteu reagent, as described (Sayeed et al., 2020). One mL of ethanolic extract was mixed separately with 10 mL of deionized water and 1.5 mL undiluted Folin Ciocalteu's reagent. After 5 min, 4 mL sodium carbonate (Na_2CO_3) (20%, w/v) was added, and volume was adjusted to 25 mL

with deionized water. The mixture was incubated at 45°C for 30 min in a water bath and the absorbance was measured at 765 nm in UV-Vis Spectrophotometer (Shimadzu Scientific Instruments, UV-2700i). The assay was performed in triplicates. Calibration curve was plotted using Gallic acid as reference standard and the results were expressed as milligram gallic acid equivalents (mg GAE [gallic acid equivalent])/g of extract.

2.5.4 Determination of In-vitro antioxidant activity of onion waste

In-vitro antioxidant activity of ethanolic onion waste extract was determined using two different methods: 2,2-diphenylpicrylhydrazyl (DPPH) free radical scavenging activity, and Hydroxyl radical scavenging activity (HRSA). Apart from ethanolic extract, the methanolic and hexane extracts were also used for the determination of *in-vitro* antioxidant activity of onion waste. Tests were carried out in triplicates.

2.5.4.1 DPPH radical scavenging activity

The free radical scavenging activity of three different onion extracts and ascorbic acid as positive control was measured in terms of hydrogen donating or radical-scavenging ability using the stable radical DPPH by the method as described with slight modifications (Sayeed and Thakur, 2019). 3 mL of freshly made DPPH solution (0.004%) in ethanol were mixed with 2 mL of each extract and the control at varying concentrations (100, 50, and 10 g/mL). The reaction was kept for 30 min and the absorbance was measured at 515 nm using a spectrophotometer. The experiments were carried out for triplicates. The colour becomes purple to yellow, indicating the scavenging potential of the extract. The percentage inhibition of DPPH free radical scavenging activity was calculated using the following equation:

$$\text{Percentage inhibition (\%)} = \left(\frac{A_0 - A_s}{A_0} \right) \times 100$$

Where; A_0 =absorbance of negative control, A_s =absorbance of sample.

2.5.4.2 Hydroxyl radical scavenging activity (HRSA)

The hydroxyl scavenging activity of three different onion extracts in methanol, hexane and ethanol was determined by the method as described (Sayeed et al., 2020). The reaction mixture contained 200 mL of pre-mixed ferric chloride (100 mM) and

Ethylenediaminetetraacetic Acid (EDTA) (100 mM) solution (1:1; v/v), 500 mL of 2-deoxyribose (2.8 mM) in phosphate buffer (50 mM, pH 7.4), 100 mL of H₂O₂ (200 mM). A 100 L addition of 300 mM ascorbate started the reaction, which was then allowed to proceed for 1 hour at 37°C. After adding 0.5 mL of the reaction mixture to 1 mL of TCA (Trichloroacetic acid) (2.8% w/v; aqueous solution), the reaction mixture received 1 mL of 1% aqueous TBA (Thiobarbituric acid). The mixture was heated on a boiling water bath for 15 min and the absorbance at 532 nm was measured in comparison to a blank (the same solution but without reagent). The percent inhibition was calculated by the following equation:

$$\text{Percentage inhibiting activity} = \frac{A_0 - A}{A_0} \times 100$$

Where; A=absorbance of sample, A₀=absorbance of control.

2.6 Determination of anti-microbial activity of onion waste

2.6.1 Preparation of two different onion waste extract and antibiotic susceptibility

An equal weight about 50 g of powdered onion waste was dissolved in 250 mL of ethanol, and hexane separately and kept overnight at shaker for proper mixing. Finally, it was filtered through Whatman filter paper no. 1 and concentrated in the rotary vacuum evaporator to obtain a final yield of 9 mL/50 g for antimicrobial activity testing. Streptomycin (1 mg/mL of sterile distilled water) was used as standard antibiotic and positive control (Singh and Katoch, 2020).

2.6.2 Microbial strains

Microorganisms were obtained as lyophilized cultures from Microbial Type Culture Collection (MTCC, Chandigarh, India). Microorganisms were as follows: MTCC/9760 of Gram-positive bacteria, *Staphylococcus aureus* and MTCC/1302 of Gram-negative bacteria, *Escherichia coli*.

2.6.3 Preparation of test microorganisms

Test bacteria were grown on nutrient agar slants for 24 hrs at 37°C and then stored at 4°C. The inhibitory activity of extracts, and antibiotic susceptibility was tested against bacteria namely *Escherichia coli* and *Staphylococcus aureus* by Agar well diffusion method (Kumari et al., 2016). Pure

cultures of the test microorganisms were aseptically added to test tubes filled with sterile nutritional broth before being incubated at 37°C for 24 hours. 6mm-diameter wells in agar were drilled and inoculated with test-bacteria broth cultures (by swabbing using sterile cotton swabs). The extracts, negative control (Ethanol, Hexane respectively), and Streptomycin were transferred into the respectively labelled wells. The plates were incubated at 37°C for 24 hours in upright position and the zone of inhibition was recorded.

3. RESULTS AND DISCUSSION

3.1 Proximate composition

The proximate composition of the powdered onion waste is represented in Table 1. The Carbohydrates (70.47 g/100 g) predominated in the onion waste whereas the fat content was low (0.64±0.01 g/100 g) and protein was 8.56%.

Table 1. Proximate composition of onion waste powder per 100 g (n=3)

Parameter (g)	Onion waste powder
Moisture content	3.67±0.20
Crude protein (%N x 6.25)	8.56±0.04
Crude fat	0.64±0.01
Crude fibre	4.49±0.05
Ash content	5.00±0.21
Carbohydrates	70.47±0.47
Energy value (kcal)	321.88±5.06
Total dietary fibre (TDF)	69.06±0.21
Soluble dietary fibre (SDF)	8.88±0.08
Insoluble dietary fibre (IDF)	63.64±0.13

The value given in the table represents the mean value±SD of three individual replicates.

The onion waste powder was found to be a good source of carbohydrates (70.47%), dietary fibre (69.06%) and protein (8.56%). Kumar et al. (2022a) indicated the protein content in onion waste at around 8.3-15.6% dm (dry matter). Protein contributes to the production of hormones which regulates the body function such as growth, repair, and replacement of tear tissues of the body.

Additionally, carbohydrates serve as a substrate for the production of aromatic amino acids and phenolic compounds and act as an alternative source of glucose (Gupta et al., 2025). A higher content of carbohydrates can be beneficial to human health, as they not only serve as a primary source of energy but also play a catalytic role in various biochemical reactions during metabolism. Crude fibre content in

the onion waste was found to be 4.49 g/100 g. [Dinkecha et al. \(2017\)](#) noted the crude fibre content of onion between 3.82-5.15%. Crude fibre is recognised as functional food ingredient that acts as specific ingredient. The presence of fibre content in diet improves digestion and acts as functional food ingredient for controlling oxidative processes in food products. The consumption of crude fibre is essential for proper digestion and waste elimination from the body. Moreover, the contraction of muscular walls of the digestive tract is stimulated by fibre, thus counteracting constipation ([Melani, 2025](#)). The total dietary fibre in powdered onion waste depends on cultivars. It promotes the management of diabetes mellitus and protects the body against cardiovascular disease, colorectal cancer and obesity. The low moisture content (3.67%) in the onion waste powder reveals that the product is less prone to deterioration, and could be used for preservation, therefore, less susceptible to the action of micro-organisms. The high ash content (5%) in onion waste indicates the presence of rich mineral content in the product, highlighting nutritional significance ([Bilge et al., 2016](#); [Damanik et al., 2023](#)).

3.2 Non-structural carbohydrates

The non-structural carbohydrates of powdered onion waste are shown in [Table 2](#). The study evaluated the content of glucose, fructose and sucrose at around 4.40%, 1.75%, 1.10%, respectively.

Non-structural carbohydrates play an important role in plants responses against drought and frost stress. Glucose is the most common non-structural carbohydrate, followed by fructose, sucrose, and low-molecular-weight fructans or fructo- oligosaccharides (FOS) in onions. These are considered as main carbohydrate reserves of onion. They accumulate during bulbing and are then catabolized during regrowth and the sprout development of the bulbs. [Sidhu et al. \(2019\)](#) noted the sugar composition of freeze dried Indian red onion variety as % dry weight basis at glucose (17%), fructose (7.4%) and sucrose (11.7%). High levels of reducing sugars i.e. glucose and fructose are responsible for the more browning during frying or drying of onions. These reducing sugars take part in the fermentation process and are an important parameter for yield and productivity of the fermentation products ([Shahid et al. 2023](#)). [Cho et al. \(2021\)](#) studied the potential of developing biosugar, an alternative bee feed from onion waste that has a similar composition to that of honey. Multiple investigations

suggest that non-structural carbohydrates may be involved in the control of xylem water transport in the horticultural product.

Table 2. Non-structural carbohydrates composition in powdered onion waste (per 100 g) (n=3)

Parameters (g)	Onion waste powder
Glucose	4.40±0.01
Fructose	1.75±0.01
Sucrose	1.10±0.01

The value given in the table represents the mean value±SD of three individual replicates.

3.3 Phytochemical composition

[Table 3](#) shows the phytochemical composition of the ethanolic onion extract. The study indicated the presence of anthraquinones, anthocyanins, phenols, carbohydrates, flavonoids, glycosides, terpenoids, tannins etc., and the absence of alkaloids, sterols and saponins. The obtained phytochemical compounds possess both physiological as well as medicinal activities.

The obtained phytochemical compounds possess both physiological as well as medicinal activities. [Marefati et al. \(2021\)](#) noted that the tannins investigated in the skin of *Allium cepa* have antioxidant properties, and their presence confirms the anti-inflammatory properties in vegetables, which describes its usage to treat ulcers, earaches, and as an antitussive. Alkaloids are extremely helpful in medicine and are employed in the creation of a number of beneficial medications ([Dalhat et al., 2018](#)). Presence of alkaloids suggests that the onion waste can be utilized as an analgesic, anti-inflammatory, anticancer, antibiotic, and antispasmodic due to their existence ([Letchuman et al., 2025](#)). Saponins, which are glycosides of sterols and triterpenes, are found in more than 70 plant groups. They have been found to have antitussive properties and work as emulsifying agents ([Timilsena et al., 2023](#)). The presence of flavonoids also possesses metal chelating properties that build the stability of the product, via stopping the generation of free radicals ([Rodríguez-Arce and Saldias, 2021](#)).

3.4 Total phenolic content

Onion waste, particularly outer dry skins and peels, constitutes a high-value source of phenolic compounds. Quantitative TPC determination through the Folin-Ciocalteu method enables characterization and potential standardization of extracts for functional

use. Optimization of extraction conditions and proper solvent selection are essential for maximizing phenolic recovery, ultimately contributing to sustainable waste valorisation strategies.

Table 3. Qualitative phytochemical screening of ethanolic onion waste extract

S.No.	Test compounds	Extract test	Sample
1.	Saponins	Frothing	-
2.	Anthraquinones	Borntrager's	++
3.	Anthocyanins	Sodium hydroxide	+
4.	Carbohydrates	Fehling's	+
5.	Flavonoids	Sulphuric acid	+
6.	Glycosides	Keller-Killani	+
7.	Phenols	Ferric chloride	++
8.	Proteins & Amino Acids	Xanthoproteic	+
9.	Sterols	Liebermann-Buchard	-
10.	Tannins	Ferric chloride	+++
11.	Terpenoids	Liebermann-Buchard	+

Note: (+): Indicates the presence of phytochemicals; (-): Indicates the absence of phytochemicals; (++ & +++): Indicates the medium and high level of concentration resp.

The TPC in the ethanolic onion waste extract was found to be 320.11 mg/g GAE. Many scholars have investigated the phenols in overall onion waste. [Singh et al. \(2017\)](#) reported high concentration of total phenolic compounds (418 mg GAE/g of extract) in 70% ethanolic extract of onion waste. Onion waste has a high concentration of free phenolics, which contributes to their antioxidant and antiproliferative properties, making them an effective selection for functional foods. [Kumar et al. \(2022a\)](#) reviewed the total phenolic compounds in different composition of onion peel/skin based on different varieties, agronomic conditions of the region in which they were cultivated, and the extraction techniques used. In another study, total phenolic compounds in onion waste including skin and peel were obtained at around 19.7-415 mg GAE/g of extract. [Paesa et al. \(2022\)](#) also reported the presence of TPC (177 mg GAE/g of extract) in the onion waste.

3.4.1 In-vitro antioxidant activity

The antioxidant and free radical scavenging properties of three different onion waste extracts (Methanol, Hexane and Ethanol) are associated with their medicinal benefits. DPPH radical scavenging activity and Hydroxyl radical scavenging activity (HRSA) tests were used to assess the antioxidant activity of three distinct onion waste extracts. The antioxidant property of the extracts generated was assessed by the DPPH free-radical scavenging method which is based on the exchange of hydrogen atoms between the antioxidant and the stable DPPH free

radical diseases ([Singh et al., 2017](#); [Singh et al., 2026](#)). The DPPH and Hydroxyl radical scavenging activity (%) of ethanolic onion waste extract at concentrations of 10, 50, and 100 g/mL, ranged from 42.34% to 70.50%, 65.8 to 60.5%, respectively. Similarly, the DPPH and HRSA of methanolic onion waste extract at different 10, 50, and 100 g/mL, ranged from 43.46 to 59.19%, 59.70 to 57.60%, respectively. [Tables 4 and 5](#) presents the scavenging activity of the three onion waste extracts using the DPPH and HRSA methods respectively.

The onion waste exhibited higher levels of antioxidant activities as DPPH radical scavenging and HRSA. It was also noted that the HRSA antioxidant activity was higher as compared to DPPH radical scavenging activity. It may be due to the different antioxidant mechanisms of these molecules on the free radicals and their chemical environment. In research conducted to study the antioxidant potential of onion peel extracts using DPPH, lipid peroxidation and ferric thiocyanate method, DPPH method with ethanolic extract showed highest antioxidant activity. The high antioxidant activity of onion peel extract is attributed to the richness of organosulfur compounds, polyphenols and flavonoids in it ([Chakraborty et al., 2022](#)). [Singh et al. \(2017\)](#) noted the percent radical scavenging activity of methanol onion waste extract by using DPPH methods to be 83.7%. [Kumar et al. \(2022a\)](#) noted that ethanolic extraction was best suited for total phenolic content of onion waste considering the polarity of bio active molecules. [Masood et al. \(2021\)](#) observed that the total flavonoids and phenolic

content of ethanolic extract of onion peel were significantly higher when compared to that of onion bulb. Also, ethanolic extract of onion peel also presented better antioxidant and free-radical

scavenging activity as compared to the ethanolic extract of bulb. Antioxidant activities contribute to the beneficial health effects of phenolic compounds (Zeb, 2020).

Table 4. Percentage scavenging activity of three onion waste extracts at different concentrations at 765 nm using DPPH method

Concentration (µg/mL)	A _{Methanol}	% Scavenging activity	A _{Hexane}	% Scavenging activity	A _{Ethanol}	% Scavenging activity
10	0.805	43.4±0.31	0.787	44.7±0.17	0.821	42.3±0.17
50	0.753	47.1±0.23	0.632	55.6±0.19	0.692	51.4±0.20
100	0.581	59.1±0.31	0.496	65.1±0.17	0.482	70.5±0.18

Where, A_{Methanol}, A_{Hexane}, and A_{Ethanol} are the absorbance of methanol, hexane, and ethanol onion waste extract, respectively.

Note: The value given in the table represents the mean value±SD of three individual replicates.

Table 5. Percentage scavenging activity of three onion waste extracts at different concentrations at 765 nm using hydroxyl radical scavenging activity (HRSA)

Concentration (µg/mL)	A _{Methanol}	% Scavenging activity	A _{Hexane}	% Scavenging activity	A _{Ethanol}	% Scavenging activity
10	1.021	59.7±0.21	1.011	58.7±0.21	1.082	65.8±0.22
50	1.014	59.0±0.13	1.008	58.4±0.31	1.041	61.7±0.19
100	1.000	57.6±0.21	1.001	57.7±0.17	1.029	60.5±0.18

Note: The value given in the table represents the mean value±SD of three individual replicates.

3.5 Antimicrobial activity

The antimicrobial activity of two different onion waste extracts and antibiotic susceptibility tests results have been presented in Table 6. As compared to hexane, ethanolic onion waste extract was found to be significant in inhibiting test microorganisms (Figure 2). Least inhibitory effect was observed in case of hexane extract of onion waste. Standard antibiotics caused higher levels of inhibition than the ethanolic and hexane extracts. Gram positive bacteria (*S. aureus*) have exhibited significant inhibitory effects compared to Gram negative bacteria (*E. coli*). The Minimum Inhibitory Concentration (MIC) values ranging from between 1,000-1,250 µg/mL. The antibiotic caused high inhibition of gram-positive bacteria than gram negative bacteria. Ethanol and hexane independently (negative control) did not cause inhibition of bacteria.

Results were evaluated by measuring the existence or nonexistence of inhibition zone around the well against the microorganism. The appearance of inhibitory zone around the well was taken as positive for antimicrobial activity. The extracts demonstrated inhibitory effect against tested bacterial strains.

Plant extracts are known to possess antimicrobial activity, asserting their role in combating microbial infections. The ethanolic extract of the onion waste showed greater antimicrobial

activity against gram-positive bacteria (*S. aureus*) proving its potential in controlling food poisoning diseases. The findings align with the results of the study by Puišo et al. (2023) who investigated the antimicrobial activity of the red-onion-peel-extract hydrogels and films containing silver nanoparticles were the most effective against *Staphylococcus aureus*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Pseudomonas aeruginosa* bacteria. Bag and Chattopadhyay (2015) investigated the antimicrobial effect of *A. cepa* against *E. coli* and *S. aureus* and reported the larger inhibitory effect on *S. aureus* than on *E. coli*. Naqvi et al. (2020) reported the absence of inhibition zone against *Bacillus cereus*, *Bacillus megaterium*, and *Staphylococcus aureus*.

Table 6. Antimicrobial activity of onion waste and Streptomycin

S. No.	Treatment	Inhibition of test bacteria (mm)	
		<i>S. aureus</i>	<i>E. coli</i>
1	Streptomycin	3.6	3.5
2	Ethanol	0	0
3	Hexane	0	0
4	Extract (Ethanol + Onion waste)	3.2	2.2
5	Extract (Hexane + Onion waste)	1.8	1.1

Plant extracts are known to possess antimicrobial activity, asserting their role in combating microbial infections. The ethanolic extract of the onion waste showed greater antimicrobial activity against Gram-positive bacteria (*S. aureus*) proving its potential in controlling food poisoning diseases. The findings align with the results of the study by Puišo et al. (2023) who investigated the antimicrobial activity of the red-onion-peel-extract hydrogels and films containing silver nanoparticles

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Figure 2. Antimicrobial activity of ethanolic extract on *Staphylococcus aureus*

4. CONCLUSION

The rapid expansion of global onion production and processing has led to the accumulation of substantial agro-industrial residues, presenting significant challenges for environmental sustainability and waste management. In alignment with circular economy principles, the valorization of onion-derived waste into functional food ingredients represents a sustainable pathway for reintegrating biomass into value chains. The present study provides a comprehensive characterization of onion waste, revealing its richness in carbohydrates, proteins, and dietary fibre, along with a diverse array of bioactive phytochemicals including flavonoids, tannins, glycosides, anthocyanins, terpenoids, and other phenolic compounds. The demonstrated antioxidant and antimicrobial activities further highlight its functional relevance.

The incorporation of onion processing by-products into food systems as powders, extracts, and microencapsulated formulations underscores their potential to enhance nutritional quality, antioxidant

capacity, and prebiotic functionality. Such strategies exemplify circular bio resource utilization by converting processing residues into high-value functional ingredients. However, the large-scale implementation of onion waste reutilization remains complex and requires robust scientific validation of health claims to ensure regulatory compliance and consumer acceptance. Future in vitro and in vivo investigations are essential to elucidate bioavailability, stability, and interactions within complex food matrices. Advancing research in this domain will accelerate innovation in the food sector while promoting sustainable development through the circular and resource-efficient utilization of agricultural by-products.

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AUTHOR CONTRIBUTIONS

Experimental run, Data Collection, Writing manuscript Original Draft: Anila Zahid; Conceptualization, Methodology, Manuscript Review and Editing: Renu Khedkar; Visualization, Supervision: Shashi Sharma; Analysis, Manuscript Review and Editing: Sanjay Rajput.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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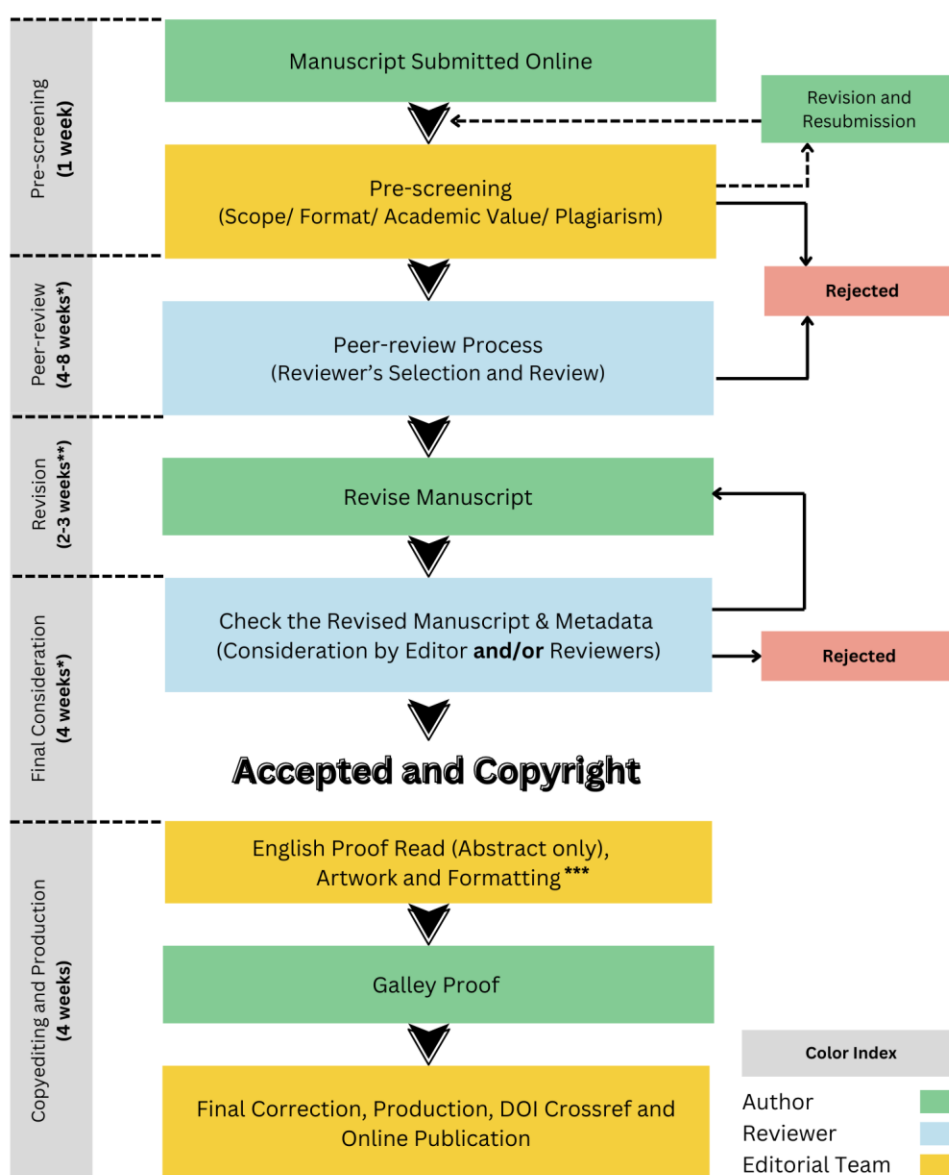
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Intergovernmental Panel on Climate Change (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories: Volume 1-5. Hayama, Japan: Institute for Global Environmental Strategies; 2006.

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