

Multi-Sensor Remote Sensing and GIS for Potential CO₂ Leakage Mapping in Gundih CCUS Field

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Manuscript received: 31 July 2026; Received in revised form: 6 September 2026; Accepted: 9 September 2026

Abstract

Geological caprock integrity is critical for preventing gas migration to the surface in carbon sequestration sites. This study evaluated surface gas escape pathways by integrating multi-sensor spatial datasets in the Gundih area, Central Java. Lineament networks were extracted from national digital elevation models (DEMNAS) to calculate Fault Fracture Density (FFD), representing structural conduits. Surface conditions and thermal anomalies were assessed independently using the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) derived from satellite imagery. Rather than relying on weighted overlay modeling, a qualitative spatial correlation approach was utilized to evaluate the interplay between structural deformation, vegetation cover, and thermal behavior. The results indicate that high-density FFD zones predominantly align along Northwest–Southeast and Northeast–Southwest structural trends. Spatial cross-analysis reveals that localized thermal anomalies (elevated LST) coincide with high-FFD fracture zones, even in areas characterized by dense vegetation (high NDVI), potentially indicating that localized thermal responses are associated with subsurface structural pathways rather than land-surface solar exposure. These findings demonstrate that integrating FFD, NDVI, and LST without arbitrary weighting provides an objective preliminary screening baseline for prioritizing caprock containment monitoring zones in subsurface storage projects.

Keywords: Caprock Integrity; Fault Fracture Density; Land Surface Temperature; Spatial Correlation; Vegetation Index.

Citation: Putra, T. K., Rahmanto, R., & Syahrbanu, S. (2026). Multi-Sensor Remote Sensing and GIS for Potential CO₂ Leakage Mapping in Gundih CCUS Field. *Jurnal Geoelebes*, 10(2): 359–370, doi: 10.70561/geocelebes.v10i2.53140

Introduction

Ensuring caprock containment security against buoyant gas migration remains a critical technical challenge in subsurface carbon sequestration projects (Zhang et al., 2020), such as the Gundih Carbon Capture, Utilization, and Storage (CCUS) field in Central Java (Tsuji et al., 2014; Santoso et al., 2019; Sule et al., 2019). Structural discontinuities, particularly fault networks and localized fracture systems within caprock formations, act as primary fluid conduits facilitating vertical gas escape toward the surface (Zhang et al., 2020). Consequently, identifying potential surface leakage pathways and evaluating high-

density fracture zones are essential prerequisites for establishing containment baselines and mitigating environmental risks in ongoing geological storage operations (Chen et al., 2019; Thiruchittampalam et al., 2022).

Conventionally, caprock integrity and structural leakage risks are evaluated using 3D seismic horizon interpretation, well-log fracture characterization, and subsurface geomechanical modeling (Tsuji et al., 2013; Bohloli et al., 2018). While these subsurface techniques provide high vertical resolution at depth, their spatial coverage across regional scales is often limited and economically prohibitive for continuous

surface monitoring (Garain et al., 2019). To address this, satellite remote sensing approaches such as Fault Fracture Density (FFD) derived from digital elevation models have been increasingly utilized to map regional structural conduits (Inoh et al., 2023; Rafiq et al., 2025). Furthermore, Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) extracted from satellite imagery offer valuable surface proxies for detecting localized thermal and environmental anomalies (Avdan & Jovanovska, 2016; Gemitzi et al., 2021). In addition, microwave remote sensing and polarimetric Synthetic Aperture Radar (SAR) decomposition provide complementary insights into physical surface roughness and structural lineament detection (Zahratunnisa et al., 2025).

Despite these advancements, remote sensing-based leakage monitoring has commonly focused on individual surface responses, such as vegetation stress or spectral alteration, or on specific structural and thermal indicators. Thiruchittampalam et al. (2022), for example, evaluated remote-sensing techniques for detecting CO₂ leakage primarily through vegetation stress, while Chen et al. (2019) reviewed the use of remote sensing for monitoring vegetation responses to CO₂ leakage at Carbon Capture and Storage (CCS) sites. Zhang et al. (2020) further reviewed a broad range of remote sensing techniques for CCS leakage monitoring, including the deployment of Raman lidar for surface CO₂ leak detection (Kim et al., 2018). These studies demonstrate the potential of remote sensing for leakage detection but also highlight the complexity of distinguishing leakage-related surface responses from other environmental effects. Although structural density and surface thermal anomalies have also been investigated as indicators of subsurface fluid pathways in other geological settings (Hidayat et al., 2023; Iqbal & Juliarka, 2020), their spatial relationship with vegetation conditions has

not been explicitly evaluated for the Gundih CCUS field within a unified, non-weighted framework. Therefore, assessing the spatial coincidence of high FFD, elevated LST, and vegetation conditions may provide an additional basis for identifying potential leakage pathways in the study area.

To address this research gap, this study aims to identify potential CO₂ leakage pathways in the Gundih CCUS field through a qualitative spatial correlation analysis integrating DEMNAS-derived FFD, Landsat-derived LST, and NDVI. The analysis evaluates the spatial coincidence between high fracture density and localized thermal anomalies while considering vegetation conditions to distinguish potential subsurface thermal responses from land-surface environmental effects. This approach provides a non-weighted spatial framework for assessing potential leakage-prone zones and supporting caprock integrity monitoring in geological carbon storage projects.

Materials and Methods

Study Area and Geological Setting

This study was conducted in the Gundih CCUS field, Central Java, Indonesia. Gundih was selected as the study area because it represents an important site for the development of geological carbon storage in Indonesia and was investigated as the location of the country's first CCS pilot project. The field was selected based on the availability of CO₂ resources, potential storage conditions, existing facilities, and the potential to convert an existing well into a CO₂ injection well (Marbun et al., 2019). The Gundih field produces CO₂-rich natural gas, with reported CO₂ concentrations of up to approximately 21%, making CO₂ management and geological storage directly relevant to the area (Marbun et al., 2019). The geographical location and regional geological setting of the study area are presented in Figure 1. The summary of

geological and operational characteristics of the Gundih CCUS field is presented in Table 1.

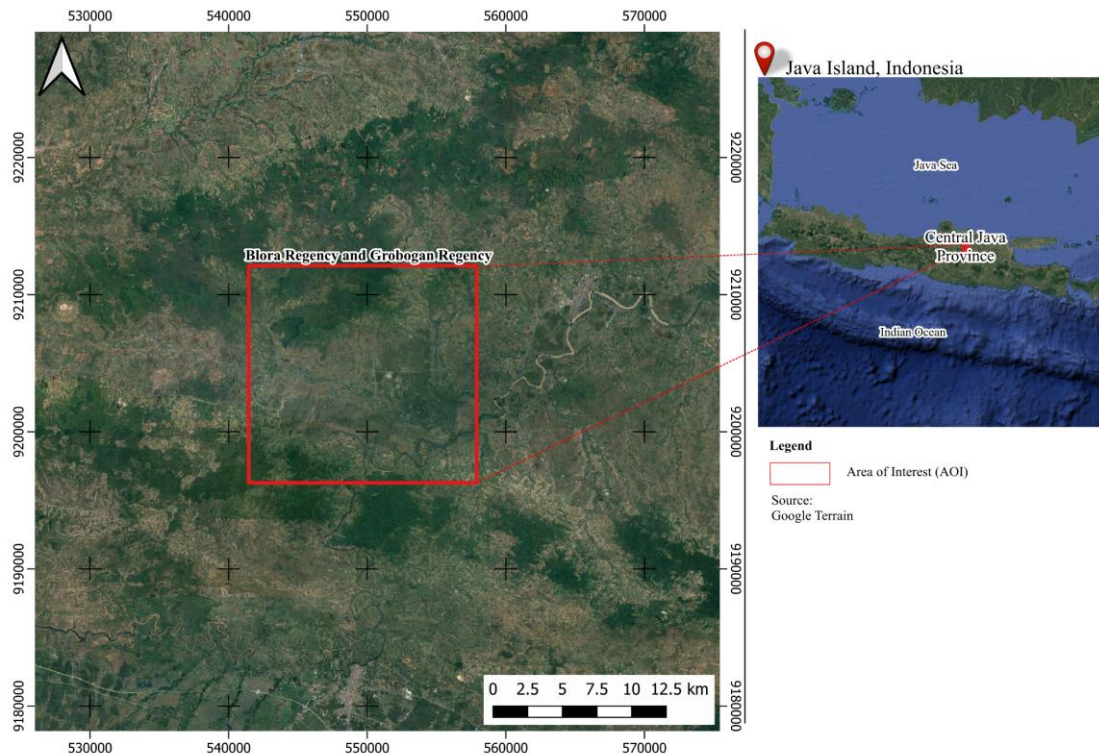


Figure 1. Geographic map and administrative location of the Gundih CCUS study area in Central Java, Indonesia. The red box delineates the primary Area of Interest (AOI), with the inset map showing its regional position on Java Island.

Table 1. Geological and operational characteristics of the Gundih CCUS field.

Parameter	Geological Specification	References
Regional Setting	Randublatung Sub-Basin (Kendeng Thrust Belt – Rembang Zone)	Sribudiyani et al. (2003)
Target Storage Reservoir	Middle Miocene Ngrayong Formation (Quartzose Sandstone)	Tsuji et al. (2014)
Primary Caprock Seal	Late Miocene Wonocolo & Pliocene Ledok Formations (Marine Claystone)	Tsuji et al. (2013)
Target Injection Depth	830 – 1,100 m True Vertical Depth Subsea (TVDSS)	Tsuji et al. (2014)
Trapping Mechanism	Anticlinal structural trapping with hydrodynamic sealing	Tsuji et al. (2013)
Primary Containment Risk	Reactivated strike-slip faults creating vertical fracture conduits	Tsuji et al. (2014)

Geologically, the Gundih field is located within the East Java Basin and the Randublatung Sub-Basin. The main storage target is the Miocene Ngrayong Formation, which consists predominantly of sandstone and has been investigated as a potential CO₂ injection reservoir (Tsuji et al., 2014). At the JPN-1 well, the proposed CO₂ injection interval is located at approximately 854–

862 m depth within the Ngrayong Formation (Marbun et al., 2019). The Ngrayong Formation is overlain by the low-permeability Wonocolo Formation, which has been considered a sealing formation for the storage system (Tsuji et al., 2014). The regional stratigraphic succession of the study area is summarized in Table 1.

The structural setting is also important because faults and fractures may influence subsurface fluid migration and therefore need to be considered when evaluating CO₂ containment. The selection of Gundih is further supported by documented well-integrity concerns. Previous investigation of the JPN-1 well identified gas leakage and casing-integrity problems that needed to be addressed before the well could be converted into a CO₂ injector (Marbun et al., 2019). These conditions highlight the importance of evaluating potential pathways that may facilitate subsurface fluid migration. Therefore, spatial screening of surface indicators can provide a complementary baseline assessment of areas potentially associated with subsurface CO₂ migration. In this study, FFD, LST, and NDVI are integrated to evaluate their

spatial coincidence and identify areas that may indicate potential leakage pathways.

Data Sets and Processing Framework

To evaluate potential surface leakage pathways without introducing subjective weighting bias, spatial parameters were extracted independently from multi-sensor remote sensing imagery and national digital elevation models. Topographic lineaments were extracted using the high-resolution Digital Elevation Model Nasional (DEMNAS) with an 8.27 m spatial resolution (Badan Informasi Geospasial, 2018). Optical and thermal bands were acquired from Landsat 8/9 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) satellite imagery. The multi-sensor spatial datasets utilized in this study are detailed in Table 2.

Table 2. Multi-sensor spatial datasets and derived parameters utilized in this study.

Dataset / Sensor	Resolution / Spec	Primary Application
DEMNAS	0.27" (~8.1 m) Raster DEM	Topographic lineament & Raster DEM multi-azimuth hill-shades
Landsat 8/9 TIRS	30 m	Land Surface Temperature (Surface thermal anomaly identification)
Landsat 8/9 OL	30 m Multispectral	NDVI calculation (surface modifier proxy)

Fault Fracture Density (FFD) Extraction

Regional structural lineaments were extracted automatically and manually verified using DEMNAS raster imagery (Badan Informasi Geospasial, 2018). Lineament networks were processed to calculate FFD, defined as the total lineament length per unit surface area (km/km²) (Inoh et al., 2023; Rafiq et al., 2025). The spatial calculation is governed by Equation (1):

$$FFD = \frac{\sum_i^n L_i}{A} \quad (1)$$

where $\sum_i^n L_i$ is the total cumulative length of extracted structural lineaments within a given grid cell (km), A is the area of the evaluation grid cell (km²), and FFD represents the fault fracture density expressed in km/km². Lineament density was computed using a continuous moving

window with an evaluation grid cell size of 100 m × 100 m and a search radius of 1 km.

Normalized Difference Vegetation Index (NDVI)

Surface vegetation density was mapped using optical bands from Landsat 8/9 OLI satellite imagery. NDVI was calculated to characterize land-surface cover conditions and serve as an environmental mask for thermal analysis (Xue & Su, 2017; Chen et al., 2019), following Equation (2):

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \quad (2)$$

where ρ_{NIR} represents the surface reflectance of Band 5 (Near-Infrared, 0.85–0.88 μm) and ρ_{Red} corresponds to Band 4 (Red, 0.64–0.67 μm) acquired from Landsat 8/9 OLI.

Land Surface Temperature (LST) Calculation

Surface thermal responses were quantified using the Thermal Infrared Sensor (TIRS) Band 10 of Landsat 8/9 (Avdan & Jovanovska, 2016; Gemitzi et al., 2021). The processing sequence involved converting digital numbers (DN) to Top of Atmosphere (TOA) spectral radiance, calculating brightness temperature (TB), and correcting for land surface emissivity (ϵ) based on NDVI proportions, as expressed in Equation (3) (Avdan & Jovanovska, 2016; Gemitzi et al., 2021):

$$LST = \frac{T_B}{1 + \left(\frac{\lambda \cdot T_B}{\rho}\right) \ln(\epsilon)} \quad (3)$$

where TB is the satellite brightness temperature (K), λ is the effective wavelength of emitted radiance (10.8 μm for TIRS Band 10), $\rho = h \cdot c / \sigma = 1.438 \times 10^{-2} \text{ m} \cdot \text{K}$ (derived from Planck's constant h , velocity of light c , and Boltzmann constant

σ), and ϵ is the unitless land surface emissivity calculated from fractional vegetation cover (Pv). The final temperature was converted to Celsius ($^{\circ}\text{C}$) by subtracting 273.15.

Qualitative Spatial Correlation Analysis

Rather than converting continuous rasters into discrete reclassified categories or applying subjective weighted overlays, this study preserves the continuous spatial values of FFD, NDVI, and LST datasets to maintain high spatial resolution. Localized thermal anomalies were isolated by identifying LST values exceeding the statistical threshold of mean plus 1.5 standard deviations ($\mu + 1.5\sigma$) (Hidayat et al., 2023). Direct spatial overlay was conducted to evaluate whether high FFD fracture networks directly coincide with surface thermal hotspots under dense vegetation canopy. A quantitative summary of these spatial parameters is presented in Table 3.

Table 3. Quantitative summary of spatial parameters used in the qualitative spatial correlation analysis.

Parameter	Data Type	Value Range / Representation	Interpretation
FFD	Continuous Raster	0 to $> 2.5 \text{ km/km}^2$	Spatial density of structural fracture networks
NDVI	Continuous Raster	-1.0 to +1.0	Surface vegetation density and canopy cover condition
LST	Continuous / Threshold	Real Temperature ($^{\circ}\text{C}$) / Anomaly ($> \mu + 1.5\sigma$)	Surface thermal baseline and localized thermal anomalies

The complete methodological workflow illustrated in Figure 2.

Results and Discussion

Structural Lineament and Fault Fracture Density (FFD) Analysis

Lineament extraction from DEMNAS reveals marked structural heterogeneity across the Gundih field, with FFD values

reaching $> 2.5 \text{ km/km}^2$. High-density anomalies ($\geq 1.5 \text{ km/km}^2$) cluster predominantly within the eastern and southwestern sectors along dominant NW–SE and NE–SW orientations (Figure 3). This localized clustering aligns with the regional compressional deformation and strike-slip fault dynamics near the Kendeng–Rembang boundary zone (Tsuji et al., 2014; Dhara et al., 2022).

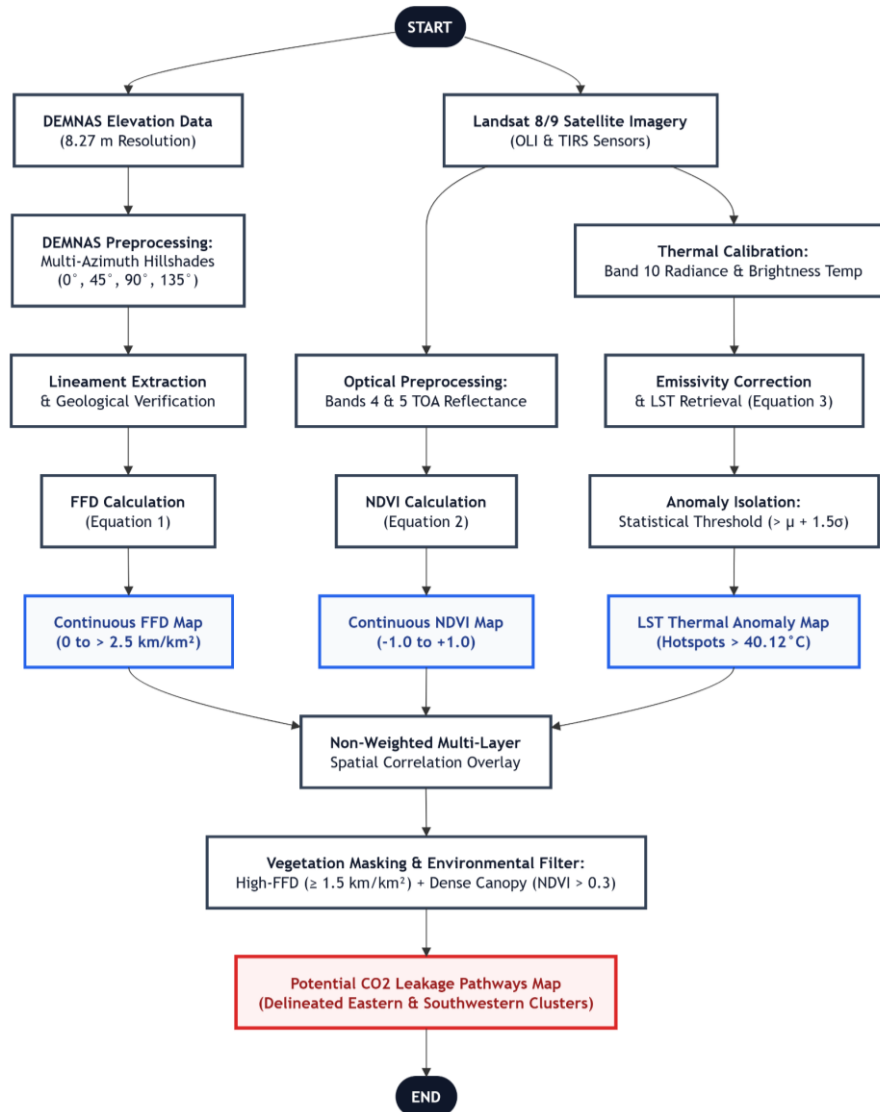


Figure 2. Methodological flowchart illustrating multi-sensor data extraction, continuous parameter processing, and non-weighted qualitative spatial correlation for potential CO₂ leakage pathway mapping in the Gundih CCUS field.

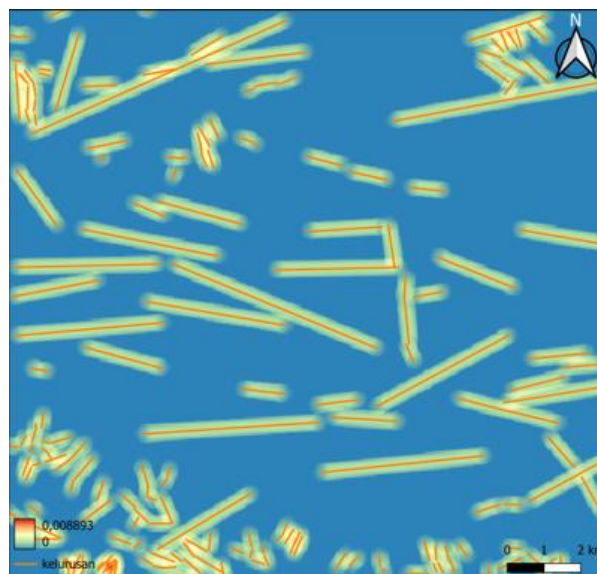


Figure 3. Continuous FFD distribution map derived from DEMNAS automatically extracted structural lineaments in the Gundih field.

In caprock integrity assessment, elevated surface lineament density highlights zones of potential mechanical weakness and secondary permeability above the target Ngrayong reservoir. However, because FFD maps surface-expressed discontinuities, these clusters represent structural susceptibility baselines rather than definitive proof of active subsurface CO₂ migration.

Surface Vegetation Canopy Assessment (NDVI)

To distinguish subsurface thermal anomalies from solar-induced ground heating, the vegetation canopy was mapped using Landsat-derived NDVI (Xue & Su, 2017; Chen et al., 2019). NDVI values ranged from -1.0 to +1.0. Densely vegetated agricultural and forested zones (NDVI > 0.3) covered the majority of the area, while areas with low NDVI (< 0.2) represented bare soil, roads, and riverbeds (Figure 4).

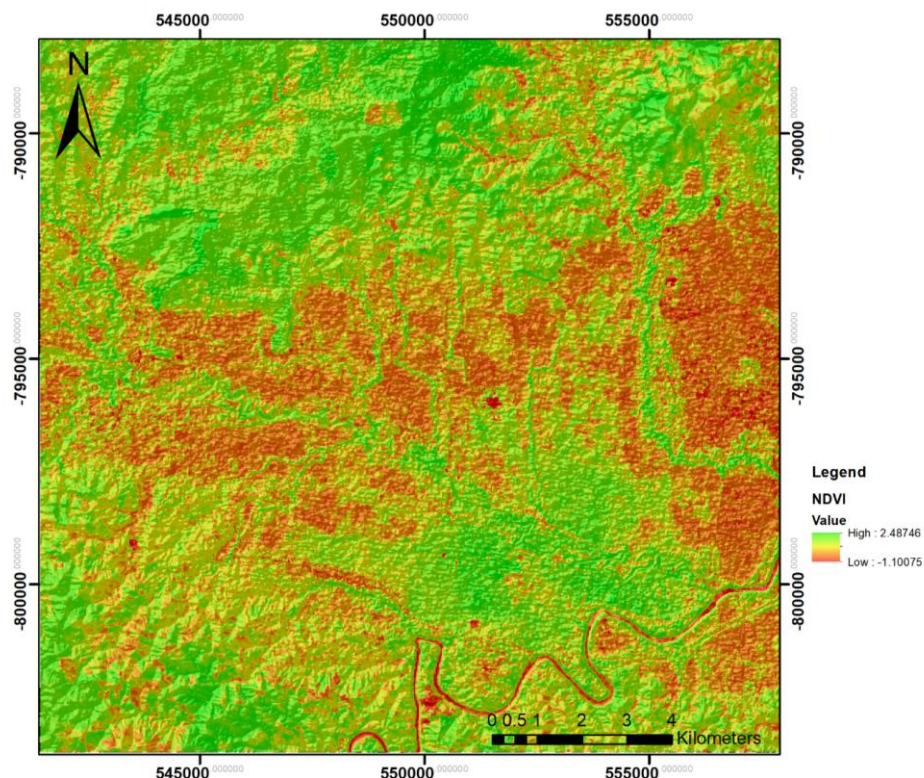


Figure 4. Continuous NDVI map representing surface canopy density across the study area.

In the context of potential CO₂ leakage assessment, vegetation information is useful as a surface-condition constraint rather than as direct evidence of leakage. Elevated soil CO₂ concentrations can affect vegetation condition, but vegetation responses may also result from non-CO₂ factors such as water availability, nutrient conditions, and land management (Chen et al., 2019). Therefore, areas with dense and relatively healthy vegetation provide an important context for interpreting thermal anomalies because elevated surface temperature in such areas is less likely to be

explained simply by exposed bare ground. In this study, NDVI is consequently used together with FFD and LST to evaluate whether localized thermal anomalies occur within structurally complex areas while accounting for vegetation cover.

Land Surface Temperature (LST) and Thermal Anomaly Isolation

The spatial distribution of LST in the Gundih CCUS field ranged from 29.52 °C to 45.41 °C, with a mean (μ) of 36.28 °C and a standard deviation (σ) of 2.56 °C (Avdan & Jovanovska, 2016). By applying

the statistical anomaly threshold ($> \mu + 1.5\sigma$), localized thermal hotspots exceeding 40.12 °C were isolated (Hidayat et al., 2023). These thermal anomalies manifested

as discrete spatial clusters concentrated within the eastern and southwestern sectors (Figure 5).

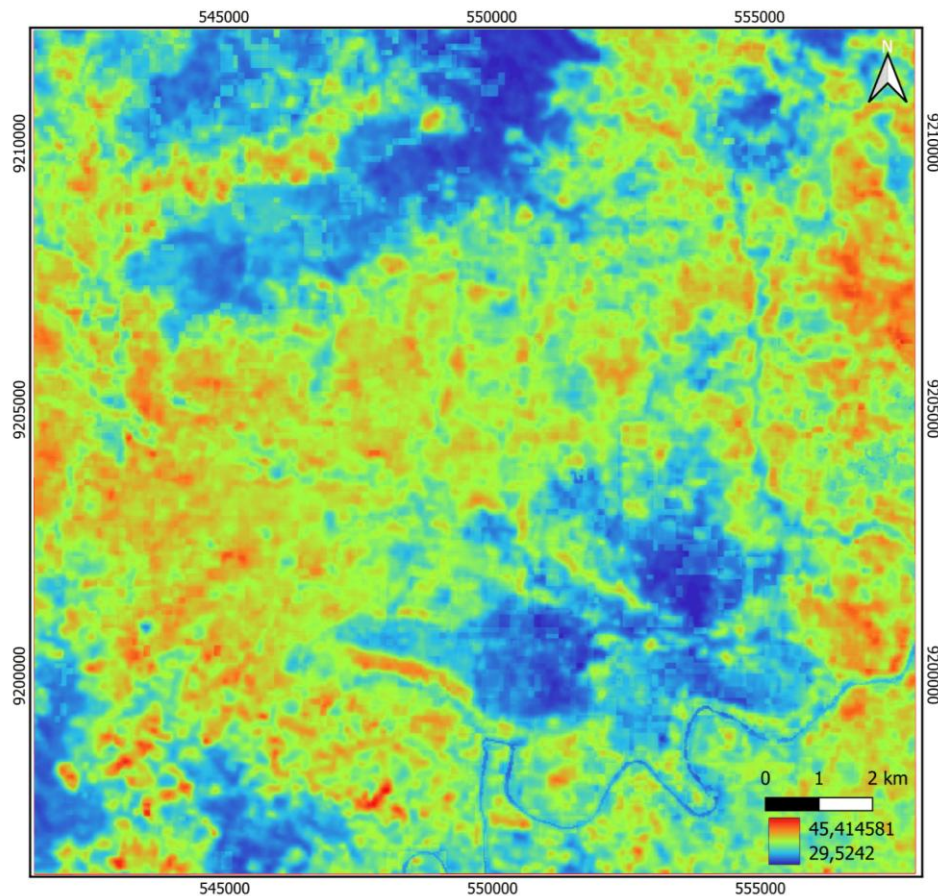


Figure 5. LST map integrated with isolated thermal anomaly outlines (> 40.12 °C).

In geological carbon storage settings, localized surface thermal anomalies along structural corridors typically reflect advective heat transport driven by ascending deep fluids or localized geothermal flux variations along permeable fault conduits (Thiruchittampalam et al. 2022). When formation fluids or gases migrate upward through breached seal zones, they create subtle temperature contrasts relative to surrounding ambient terrain. However, because surface thermal responses are not uniquely diagnostic of CO₂ leakage and can be influenced by solar insolation and surface moisture, their presence alone is insufficient to confirm leakage. Therefore, the spatial concentration of these thermal anomalies warrants direct cross-comparison with structural discontinuity networks (high-

FFD zones) to evaluate potential leakage pathways without overstating unverified subsurface migration.

Integrated Qualitative Spatial Correlation for Potential CO₂ Leakage Pathways

The integrated spatial correlation overlays DEMNAS-derived FFD, Landsat LST anomalies, and NDVI canopy constraints to evaluate structural containment risks above the Gundih CCUS complex without applying subjective weighting schemes. The rationale for the selected parameter thresholds is grounded in empirical statistical separation. The FFD threshold of ≥ 1.5 km/km² isolates the upper quartile of structural deformation, capturing intense fracture corridors associated with reactivated fault zones. The LST anomaly

threshold ($> \mu + 1.5\sigma$, exceeding $40.12\text{ }^{\circ}\text{C}$) delineates discrete thermal hotspots that deviate significantly from the regional background mean of $36.28\text{ }^{\circ}\text{C}$. Furthermore, the NDVI threshold of > 0.3 defines closed and semi-closed canopy cover, effectively masking solar-induced

heating artifacts typically found in exposed bare soils, roads, and riverbeds. Spatial cross-analysis demonstrates that delineated thermal anomalies in the eastern and southwestern sectors directly coincide with high-FFD fracture corridors, as delineated in Figure 6.

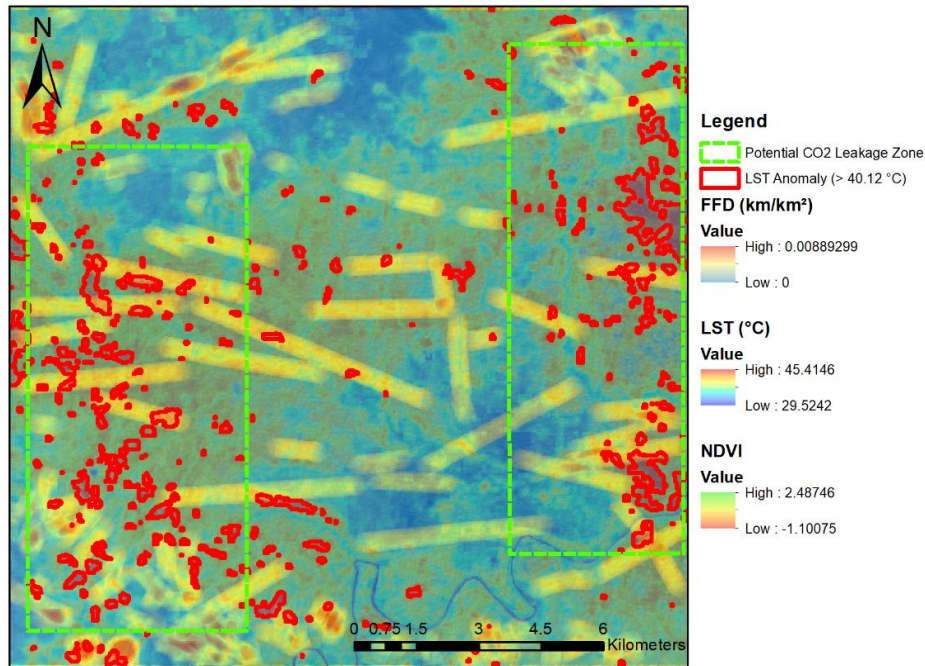


Figure 6. Qualitative spatial correlation map integrating FFD, LST anomalies, and NDVI over DEMNAS hillshade, delineating potential CO₂ leakage pathways in the Gundih field.

The spatial coincidence between high FFD and elevated LST under dense vegetation cover is geologically significant when evaluated against the subsurface architecture of the Gundih field. The target storage reservoir within the Middle Miocene Ngrayong Sandstone is situated at depths of 830–1,100 m TVDSS, overlain by the marine claystones of the Wonocolo Formation acting as the primary regional seal. Structurally, the delineated NW–SE and NE–SW anomaly trends align with reactivated strike-slip fault corridors characteristic of the Kendeng–Rembang boundary zone. In this setting, localized fracture clustering may compromise the mechanical integrity of the overlying Wonocolo mudstones, creating secondary vertical permeability networks that facilitate advective fluid or geothermal heat transport toward the surface.

Nevertheless, remotely sensed surface thermal responses cannot be uniquely attributed to subsurface CO₂ seepage. Non-geological environmental factors, including localized soil moisture deficits, agricultural variations, and seasonal insolation, can also produce elevated surface temperatures. Consequently, the delineated spatial clusters represent structural susceptibility pathways and prioritization screening targets rather than confirmed active CO₂ leakages. These findings establish a baseline for subsequent field monitoring campaigns, wherein direct in-situ soil-gas CO₂ concentration profiling, geochemical flux measurements, and shallow geophysical surveys are required to validate actual fluid migration along these structural corridors.

Conclusion

This study demonstrates a non-weighted, multi-sensor spatial screening framework integrating Fault Fracture Density (FFD), Land Surface Temperature (LST), and the Normalized Difference Vegetation Index (NDVI) to delineate potential structural leakage pathways in the Gundih CCUS field. DEMNAS-derived lineament extraction identified concentrated high-FFD corridors (≥ 1.5 km/km²) trending primarily NW–SE and NE–SW, conforming to the regional compressional and strike-slip fault patterns near the Kendeng–Rembang boundary zone. Independent satellite thermal processing isolated discrete statistical hotspots (> 40.12 °C) that spatially coincide with these dense fracture networks in the eastern and southwestern sectors, even beneath dense vegetation canopies (NDVI > 0.3).

From a caprock integrity perspective, these spatial overlaps highlight zones where secondary fracture permeability may compromise the mechanical sealing capability of the marine claystones of the Wonocolo Formation above the target Middle Miocene Ngrayong Sandstone reservoir (injection depth: 830–1,100 m TVDSS). However, because satellite remote sensing provides indirect surface observations that can be influenced by meteorological variations and soil moisture dynamics, these indicators cannot independently confirm active subsurface CO₂ escape. Consequently, the delineated anomalies serve as preliminary structural susceptibility pathways and prioritization baselines for future monitoring campaigns. Direct ground-truthing including in-situ soil-gas CO₂ concentration profiling, geochemical flux surveys, and high-resolution shallow geophysics remains imperative to validate actual fluid migration along these prioritized structural corridors (Kim et al., 2018).

Acknowledgements

The authors express their sincere gratitude to the Geospatial Information Agency (BIG) of Indonesia for providing the DEMNAS datasets, as well as NASA and the U.S. Geological Survey (USGS) for making the Landsat satellite imagery publicly accessible. Special thanks are extended to the Department of Geological Engineering, Universitas Pertamina for providing spatial analysis facilities, software support, and academic guidance throughout this research. The authors would also like to thank colleagues and technical supporters who contributed valuable insights during data analysis and manuscript preparation.

Author Contribution

Tirta Khayru Putra: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Ridwan Rahmanto:** Conceptualization, Validation, Writing – Review & Editing, Supervision. **Syahrbanu:** Software, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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