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ANALYSIS OF KARST ROCK DESERTIFICATION IN THE TROPICAL KARST REGION OF GUNUNG SEWU, TEPUS, GUNUNGKIDUL

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ABSTRACT

This study investigates the spatial dynamics of Karst Rock Desertification in the tropical karst region of Tepus District, Gunungkidul Regency, using Sentinel-2A imagery and remote sensing indices including NDVI, NDRI, FVC, and Fr. Although various studies have examined KRD in different karst regions using NDVI or NDRI individually, few have integrated multiple indices to capture both vegetation degradation and rock exposure simultaneously. Moreover, most previous studies rely on medium-resolution imagery like Landsat, which limits spatial detail, and rarely focus on the tropical karst of Indonesia. KRD, characterized by soil degradation and vegetation loss in karst landscapes, poses significant ecological threats due to its rapid and often irreversible impacts. The research employed a quantitative descriptive method combined with spatial-temporal analysis using Google Earth Engine and ArcGIS to assess land cover changes between 2019 and 2024. The analysis focused on identifying rock desertification by utilizing NDVI with FVC and the NDRI with FR. Field observations validated these findings, showing clear distinctions in soil depth and vegetation between degradation levels. The results showed significant changes in vegetation cover and rock exposure between 2019 and 2024. The Non-Rocky Desertification area decreased from 25.65% to 9.39%, while the Potential Rocky Desertification zone increased from 73.75% to 90.12%. In terms of vegetation, the “Nothing” category rose from 6.42% to 2.51%, while Moderate vegetation cover declined from 23.20% to 23.51%, and Extremely Severe decreased from 9.68% to 19.11%. These findings indicate that approximately 40% of the study area is now affected by moderate to severe desertification, emphasizing the urgent need for conservation and sustainable land management. The study highlights the critical role of vegetation management and sustainable land use to curb the advancement of desertification. These findings contribute to understanding karst ecosystem vulnerability and inform future ecological restoration strategies.

Keywords: *Karst Rock Desertification; Remote Sensing; Vegetation Index; Rock Index; Gunungkidul*

INTRODUCTION

Karst is a landform formed from the process of dissolving carbonate rocks. Globally, karst occupies about 15.2% of the land area, with the largest proportion of area in Asia (8.35 million km²) (Goldscheider et al., 2020). Its main distribution includes Southwest China–the Indochina Peninsula, Europe, Central Asia, Central America, and North America (Stevanović, 2018). The karst area in Indonesia alone covers 0.8% of the total land area, or about 15.4 million hectares(Cahyanti & Agus, 2017). In terms of population, about 1.18 billion people live in karst regions worldwide, with the highest number in Asia at 661.7 million, and the percentage (Taminskas, Paskauskas, Zvikas, & Satkunas, 2006).

Karst is a vulnerable and vital ecosystem to disturbance, so it is very susceptible to ecosystem degradation (Kang, Shen, Li, Huang, & Chen, 2024). Uneven land cover tends to limit vegetation development, so the vegetation that grows is usually fragmented and dispersed (Hou & Gao, 2020). Therefore, damage to the soil and vegetation in karst areas cannot be restored in a short time, thus disrupting the overall balance of the ecosystem.

One of the main problems that arise in karst ecosystems is the opening of bedrock layers after the soil layer has degraded, both due to natural factors and human activities. This phenomenon is known in the literature as Karst Rocky Desertification (KRD), which can be simply interpreted as the process of land degradation in karst (Liu, Zhou, Jia, Yue, & Peng, 2020a).

KRD occurs when land cover decreases significantly due to deforestation and erosion, leading to an increase in the surface of open rock (Zhou & Chen, 2025). In various studies, human activities such as intensive agriculture, overgrazing, extreme climatic events, and land conversion were cited as the main causes that accelerated the occurrence of KRD (Mandal & Roy, 2024; Xiong et al., 2009; Zucca, Fleiner, Bonaiuti, & Kang, 2022). Human activities are the main factor in the intensive land-use change (42%-68%) (Al Khoury et al., 2023) that impacts karst ecosystems (Palacios-Cabrera, Valdes-Abellan, Jodar-Abellan, & Rodrigo-Comino, 2022). This has consequences for ecology, namely changing vegetation, landscape, ecosystem structure, and degradation in karst areas (Niu, Zhang, Liang, & Huang, 2022).

The impacts caused by the KRD include environmental and economic problems, such as increased risk of landslides, floods, and accelerated erosion (Xiaxia Lu, Sheng, & Luo, 2024a). KRD is a global problem that affects many areas of karst landscapes, including western

Canada, southern Italy, and southwestern China (Liu, Zhou, Jia, Yue, & Peng, 2020b; Xiaxia Lu, Sheng, & Luo, 2024b). Karst Gunungsewu was identified as the karst area with the highest population density in Indonesia (Haryono et al., 2022). As part of the UNESCO Global Geopark, the area has developed into a geotourism hub that attracts both local and foreign tourists (Reinhart, Putra, & Rafida, 2023). The beauty of the landscape and the cultural richness of the local community are the main attractions, which contribute to increasing regional income and encouraging local economic development.

On the other hand, the high economic value of carbonate rocks makes the region also attractive for mining activities (Do Nascimento, Sessegolo, Berra, Da Silveira, & Sampaio, 2024). This activity is not only carried out by formal companies, but also by the community independently. Data from the Ministry of Industry and Trade noted that there are nine karst mining companies that employ 908 workers in Gunungkidul Regency. The existence of illegal mining activities that are not monitored is still ongoing and contributes to environmental damage.

The increasing intensity of human activities from both the tourism and mining sectors has caused significant ecological pressure on the Karst Gunung Sewu ecosystem, so efforts to review the ecology of Karst Gunung Sewu are needed, one of which is through the KRD approach using remote sensing and geographic information systems.

The use of remote sensing has a role in monitoring land degradation, because the observation process is fast and covers a large area, and can detect changes temporally. Remote sensing has been used to monitor phenomena such as desertification, soil salinization, and land-use change.

The study of KRD in the Gunung Sewu karst has not been done much; previous studies have only highlighted historical changes in land use(Sunkar, 2008) driven by population growth and agricultural expansion, which have led to increased soil erosion(Putra, Adji, & Haryono, 2025) and reduced vegetation cover. Other studies have analyzed KRD only with NDVI and slope approaches. Other studies in Indonesia related to KRD only use Landsat imagery and only come to NDRI(Budiyanto, 2014). This study aims to explore KRD in the Gunungsewu karst area with a case study of Tepus, Gunung Kidul District, using Citra Sentinel 2A and NDVI, NDRI, and Outcrop rock rate

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approaches. Sentinel-2A was chosen over Landsat for this study due to its superior spatial resolution (10 m in key visible and NIR bands) and higher temporal resolution (5-day revisit time at the equator), which are critical for capturing detailed variations in vegetation and exposed rock in heterogeneous karst landscapes. Additionally, Sentinel-2A provides 13 spectral bands, including a red-edge band particularly sensitive to chlorophyll content, allowing for more accurate vegetation and land degradation assessments than the standard Landsat multispectral bands.

MATERIALS AND METHODS

This research was carried out in the tropical karst area of Gunung Sewu, with a focus on case studies in the Tepus District, Gunungkidul Regency, Special Region of Yogyakarta (**Figure 1**). Tepus District, located at approximately 8.3° - 8.11° S and 110.36° - 110.43° E, is a coastal area in Gunungkidul known for its karst landscape and natural attractions.

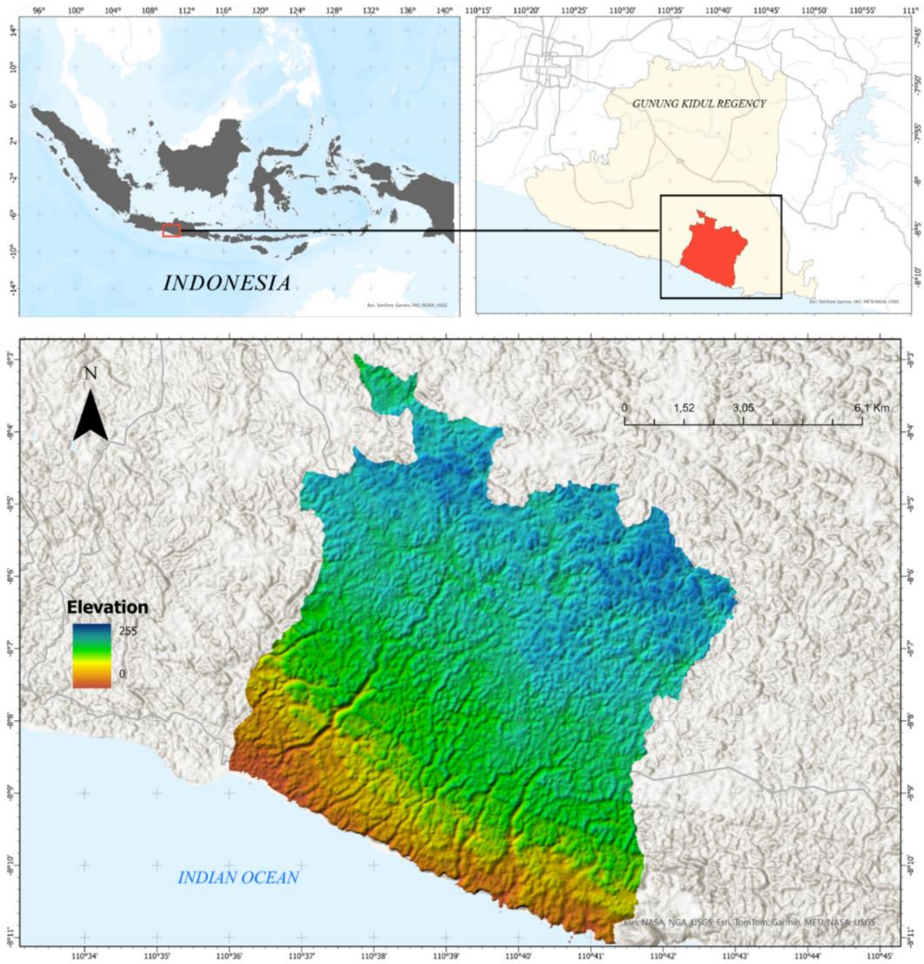

Figure 1. Research Area

This location was chosen because the Tepus District in Gunungkidul is experiencing rapid human activity, including tourism infrastructure development. Moreover, extensive land clearing for agriculture and illegal limestone mining has made the area increasingly vulnerable to environmental degradation. The approach used is spatial-based remote sensing and geographic information systems (GIS).

The method used in this study is quantitative descriptive, which aims to describe the conditions and changes in the level of rock desertification spatially and quantitatively based on temporal image comparisons. This approach allows an analysis of the distribution, intensity, and trend of changes in rock decertification in the study area.

Key data were obtained from Sentinel-2A satellite imagery for 2019 and 2024, which was processed using Google Earth Engine (GEE) for initial data processing and spatial analysis, as well as ArcGIS for further visualization and mapping. The image was used to calculate the vegetation index using the Normalized Difference Vegetation Index (NDVI) in equation (1), which is essential for quantifying vegetation cover as an indicator of land degradation. This value was then applied in the vegetation cover equation (2) to estimate fractional vegetation cover (FVC), which reflects the ground area covered by vegetation and is vital for monitoring desertification trends. The Karst Rock Desertification Index (KRDI) was derived using the Normalized Difference Rock Index (NDRI) method in equation (3), selected due to its capability to highlight exposed rock surfaces in karst regions, which are directly associated with erosion and degradation. Finally, the rock outcrop rate (Fr) was indexed in equation (4) to evaluate the proportion of exposed rock, serving as a proxy for assessing the severity of rocky desertification in karst terrains. Each formulation was chosen to capture specific aspects of environmental change in karst landscapes, allowing a comprehensive and quantifiable assessment of desertification processes.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (1)$$

$$FVC = \frac{NDVI - NDVI_R}{NDVI_R - NDVI_0} \quad (2)$$

NDVI is an index used to indicate vegetation conditions on the land surface, with NIR representing near-infrared channels and Red referring to red spectrum channels.

$$NDRI = \frac{(\rho SWIR2 - \rho Green)}{(\rho SWIR2 + \rho \text{Green})} \quad (3)$$

$$FR = \frac{(NDRI_i - NDRI_{min})}{(NDRI_{max} - NDRI_{min})} \quad (4)$$

Fr represents the rock outcrop rate, the NDRI represents the NDRI value at the second mixed pixel, the NDRI represents the maximum value of the NDRI that is entirely composed of open rock, and the NDRI represents the minimum value of the NDRI of a completely rock-free area. The risk level of rock decertification is evaluated and classified into six levels at a confidence level of 5–95%: no risk of rock decertification (level 1, Fr ≤ 20%), latent risk (level 2 20% < Fr ≤ 30%), mild decertification (level 3 30% < Fr ≤ 50%), and moderate decertification (level 4 50% < Fr ≤ 70%). Decertification of heavy rocks (level 5, 70% < Fr ≤ 90%) and decertification of very heavy rocks (level 6, Fr > 90%)(Zhang et al., 2022).

The change rate of FR and FVC throughout the study period was estimated using the formulas (5):

$$CR = \left(\frac{CR_{final\ year} - CR_{initial\ year}}{CR_{initial\ year}}\right) \times 100\ \% \qquad (5)$$

Where CR is the difference from the beginning year to the end year and $CR_{final\ year}$ and refers $CR_{initial\ year}$ to the total CR at the beginning and the last year. Image Processing shown in **Figure 2**.

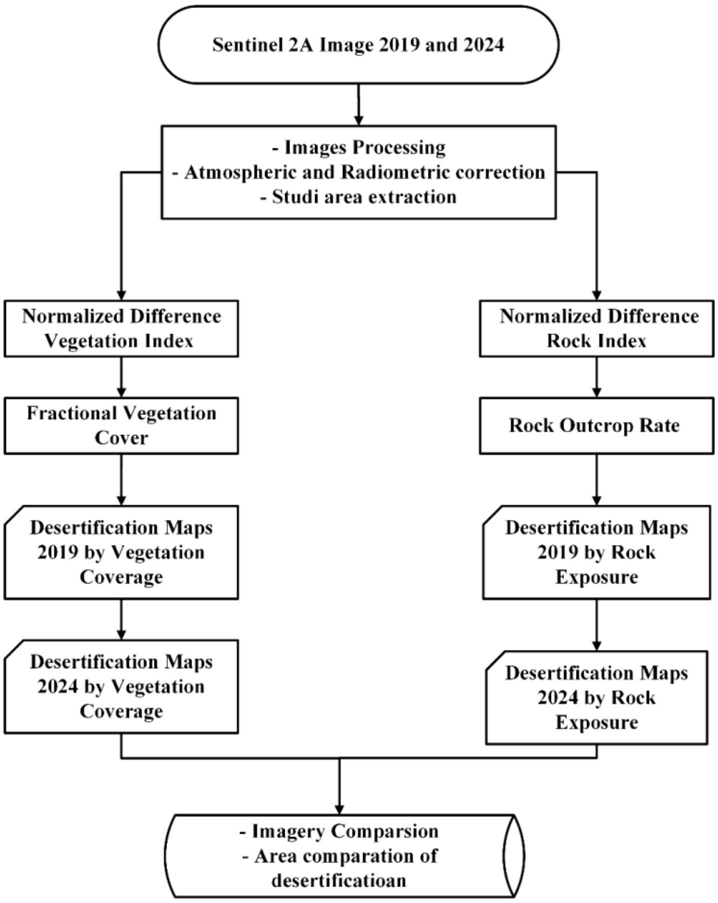

Figure 2. Image Processing

Validation was conducted at one sample point for each level of desertification. Soil depth was measured using a soil auger, while drone imagery was captured to observe the actual vegetation cover conditions. These field data were used to verify and calibrate the remote sensing interpretation results, thereby enhancing the accuracy and reliability of the analysis.

RESULTS AND DISCUSSION

Land cover in the Tepus District shifted noticeably between 2019 and 2024, reflecting increased environmental degradation. Vegetation cover variations are mapped to illustrate this desertification trend.

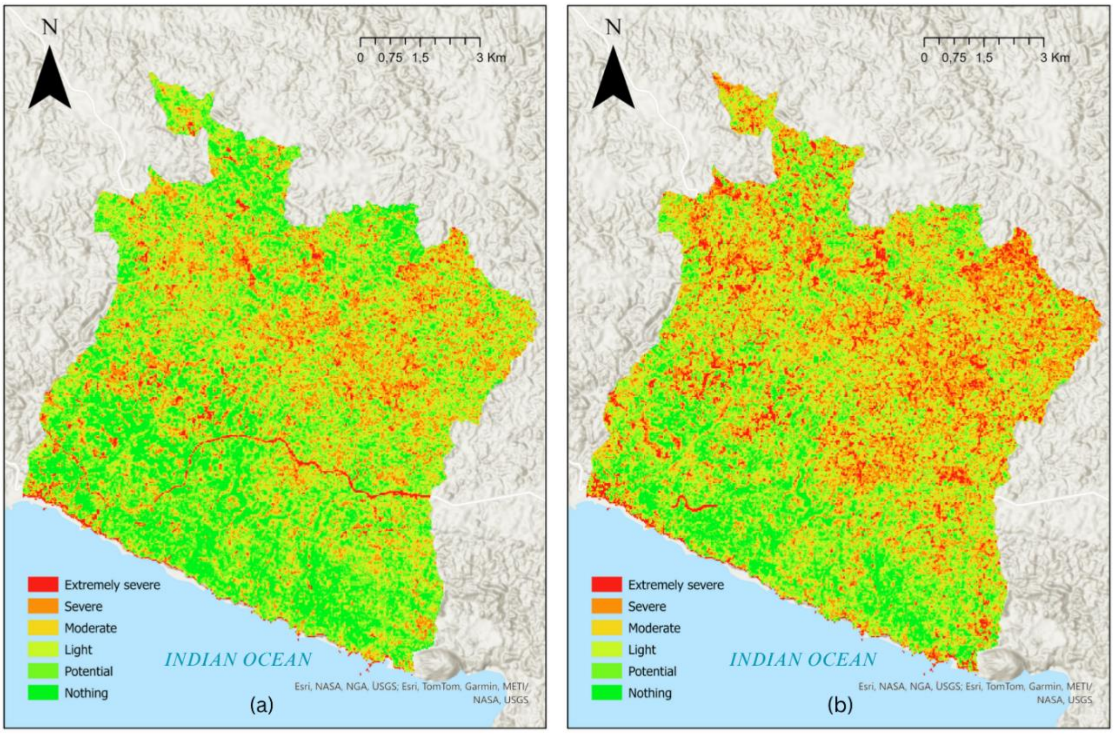

Figure 3. Desertification by Vegetation coverage (a) 2019 (b) 2024

Figure 3 compares vegetation cover for 2019 (a) and 2024 (b), namely: Nothing, Potential, Light, Moderate, Severe, and Extremely Severe, which are visualized by color gradations from dark green (dense vegetation) to red (no vegetation or very rare). The 2019 map (**Figure 3a**) shows the dominance of the Light to Moderate classes mainly in the central and southern parts of the study area, while the Severe and Extremely Severe zones appear to be scattered in the northern and hilly parts. In 2024 (**Figure 3b**), there will be an increase in the area with Severe and Extremely Severe levels, particularly in the northern and eastern parts, as indicated by the expansion of the red and orange areas. In contrast, areas with Moderate and Light classifications experienced a decline, which indicates a general decline in the quality of vegetation cover.

This decline in vegetation reflects ongoing ecological pressures, most likely due to increased land-use activities, soil erosion, and a lack of conservation interventions. These spatial changes are in line with the findings of (Xian-jian Lu, Guo, Yan, & Zhang, 2023), who show that declining vegetation cover in karst environments is often an early indicator of land degradation and rock desertification. The expansion of the Extremely Severe class is particularly concerning as it signifies a critical loss of vegetation, with a very low chance of natural recovery.

Table 1. Vegetation Coverage

Grade of Vegetation coverage	2019		2024		2019-2024	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	C	CR%
Nothing	6723900	6,42	19996200	2,51	13272300	197,4
Potential	18522900	17,70	26015400	11,56	7492500	40,4
Light	25855200	24,70	24601500	18,46	-1253700	-4,8
Moderate	24285600	23,20	19323900	23,51	-4961700	-20,4
Severe	19143000	18,29	12097800	24,86	-7045200	-36,8
Extremely severe	10128600	9,68	2624400	19,11	-7504200	-74,1

Source: Research Analysis, 2025

As shown in **Table 1**, the vegetation coverage categories in the study area shifted significantly between 2019 and 2024, indicating a reduction in rocky desertification severity. The "Nothing" category (non-desertified) increased markedly in both absolute area and proportional coverage, reflecting the recovery of previously degraded land into well-vegetated areas. The increase in both C and CR% values in this class represents substantial vegetation improvement (Qian, Qiang, Qin, Wang, & Li, 2022a).

In contrast, all rocky desertification categories—from Potential to Extremely Severe—declined in both area and proportion. The reduction in the Potential class suggests that some at-risk areas were either stabilized or improved to non-desertified conditions. Light and

Moderate classes also decreased, while Severe and Extremely Severe categories showed the most dramatic drops. Notably, the Extremely Severe class nearly disappeared by 2024, indicating successful restoration or stabilization of the most critically degraded lands during the 2019–2024 period (Cao & Wen, 2024a; Qian, Qiang, Qin, Wang, & Li, 2022b).

Ecologically, these trends reflect ecosystem recovery and a retreat of rocky desertification. Increasing vegetation cover enhances soil stability, moisture retention, and habitat quality. This aligns with findings from (Yue, Lu, Pan, & Zeng, 2024), who emphasized that high vegetation coverage correlates with reduced land degradation in karst regions. The sharp decline in severely desertified land suggests reduced soil loss and ecological risks such as erosion and biodiversity decline (Cao & Wen, 2024b).

Furthermore, the simultaneous decrease in the Potential class and all higher severity classes, along with the expansion of the Nothing class, indicates that most changes were toward recovery rather than new degradation. The absence of increases in higher severity categories between 2019 and 2024 suggests that degradation was effectively curbed (Cai et al., 2023).

Figure 4 shows the spatial distribution of rock decertification levels in the Tepus District, Gunungkidul Regency, based on FR (rock exposure) values for 2019 (a) and 2024 (b). The classification includes five levels of desertification, namely: Non-Rocky Desertification, Potential Rocky Desertification, Light, Medium, and Severe Rocky Desertification, which are visualized in color gradations ranging from light green to red.

A comparison of the two maps shows a marked change in the pattern of decertification between times. In 2024 (**Figure 4b**), the landscape will be dominated by the Potential to Medium Rocky Desertification category, particularly in the southern and western parts of the study area. However, in 2019 (**Figure 4a**), the area with the classification of Non-Rocky Desertification was the largest area, indicating a decrease in the value of the Non-Rocky Desertification area by 2024.

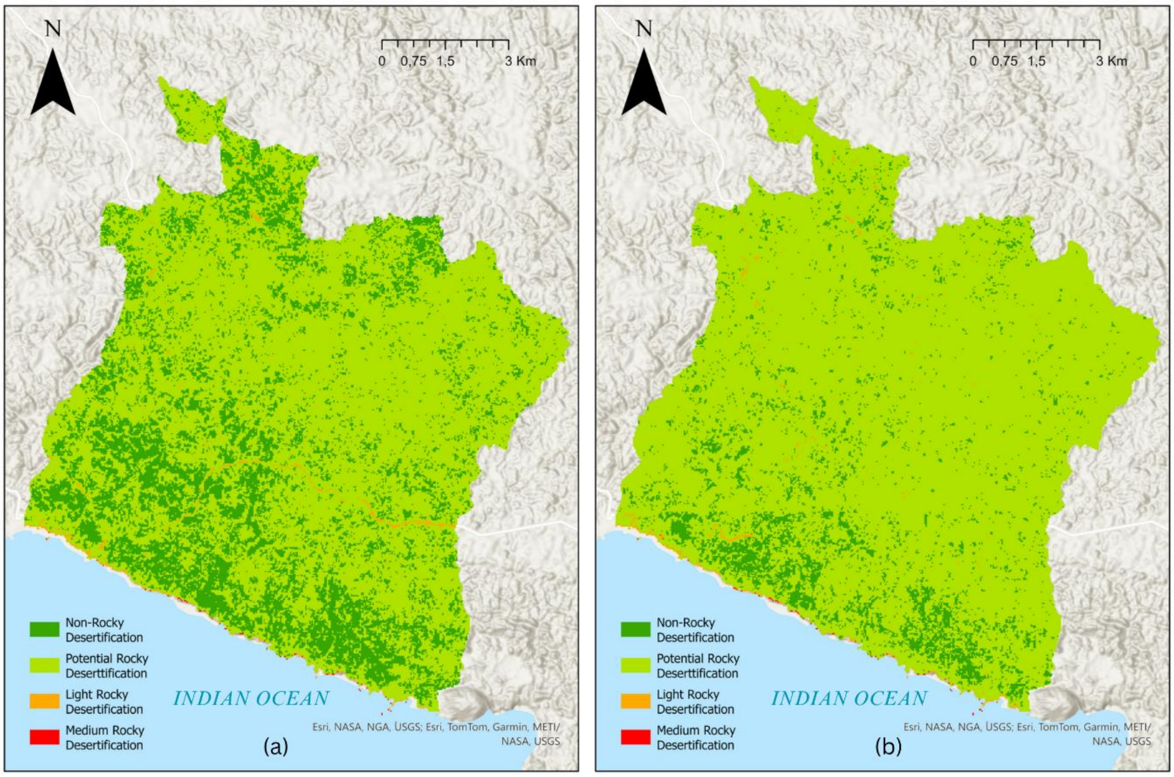

Figure 4. Rock desertification by Rock exposure (a) 2019 (b) 2024

Table 2. Rock exposure rate

Grade of Rock outcrop	2019		2024		2019-2024	
	Area (km²)	Propor-tion (%)	Area (km²)	Propor-tion (%)	C	CR %
Non-Rocky Desertification	26845200	25,65	9829800	9,39	-17015400	- 63,4
Potential Rocky Desertification	77184000	73,75	94322700	90,12	17138700	22,2
Light Rocky Desertification	582300	0,56	458100	0,44	-124200	- 21,3
Medium Rocky Desertification	47700	0,05	48600	0,05	900	1,9

Source: Research Analysis, 2025

The increase in rock exposure area observed in the Tepus karst region between 2019 and 2024 indicates a clear trend of environmental degradation. As shown in **Table 2**, the Non-Rocky Desertification category declined by 63.4%, while Potential Rocky Desertification increased by 22.2%. This shift suggests that stable vegetated areas are transitioning into vulnerable zones, driven largely by anthropogenic pressures such as limestone quarrying and vegetation loss (Putra et al., 2025).

Minor changes in the Light and Medium categories reflect a degradation pattern concentrated in the early stages, consistent with (Qian, Qiang, Qin, Wang, & Li, 2022c), who reported that early karst rocky desertification is marked by declining vegetation and increasing bare rock surfaces(Anggoro & Budiyanto, 2018). The high *C* and *CR%* values further confirm that degradation is occurring rapidly, which aligns with (D'Ettorre, Liso, Pisano, Zumpano, & Parise, 2023), who emphasized the extreme sensitivity of tropical karst to land-use changes, especially in densely populated rural areas.

Overall, these results show a significant decrease in non-decertified areas and an increase in the vulnerable category (potential), indicating an initial shift towards desertification, although not entirely in the severe category. If this trend continues without intervention, areas that are now classified as potential could develop into mild to moderate decertification in the next few years. Therefore, these results confirm the importance of vegetation management and control of human activities to prevent further increases in the rate of rock desertification.

The analysis revealed an inverse spatial pattern between NDVI-FVC values and NDRI-Fr values within the study area. Areas with high NDVI and FVC values generally corresponded to low NDRI and Fr values, indicating that dense vegetation cover is associated with low rock exposure levels. Conversely, areas with low NDVI and FVC tended to have higher NDRI and Fr values, reflecting barren rocky surfaces and limited vegetation presence.

This negative correlation highlights the land degradation process in karst ecosystems, where vegetation loss accelerates rock exposure and intensifies desertification. Field observations supported this pattern, revealing that areas with Fr values above 70% typically had shallow soil layers and almost no vegetation cover.

Furthermore, based on the study (Putra et al., 2025) approximately 40% of the study area was identified as having moderate to severe levels of Karst Rock Desertification (KRD). This finding aligns with the results presented in Table 2 of the current study, where more than 40% of the area shows moderate to high levels of degradation based on NDVI and FVC indicators. In addition, the NDRI, Fr index results indicate that over 73% of the study area falls within the Potential Rocky Desertification category, confirming that a significant portion of the landscape is vulnerable to further degradation. This consistency across studies reinforces the reliability of the remote sensing approach used and highlights the urgent need for land management interventions in karst regions.

Table 3. Environmental views across different parts of the KRD study zone in the research area.

Grade of the Rock outcrop	Soil Depth	Vegetation Coverage
Non-Rocky Desertification		
Potential Rocky Desertification		
Light Rocky Desertification		
Medium Rocky Desertification		

Source: Observation 2025

Ecologically, this relationship is significant, as vegetation plays a crucial role in stabilizing soil, retaining moisture, and supporting ecosystem balance. Its loss facilitates erosion, reduces infiltration, and enhances landscape vulnerability. Therefore, integrating both vegetation and rock exposure indices offers a more comprehensive understanding of the dynamics of karst rocky desertification in tropical environments.

Table 3 indicates that variations in the degree of karst rock desertification are distinctly observable during field surveys. Non-affected areas are generally characterized by dense vegetation and significant soil depth, whereas medium desertified regions typically exhibit sparse vegetation and shallow soil layers. Ecologically, the expansion of bedrock exposure reduces soil water retention, increases surface runoff, accelerates erosion, and hinders vegetation regeneration (Ao et al., 2025). These processes lead to biodiversity loss and diminished ecosystem functionality, potentially transforming once-productive landscapes into barren, rocky terrain. To mitigate this trend, targeted ecological restoration, such as karst-adapted reforestation and sustainable land-use planning, is essential for slowing rocky desertification in the Gunung Sewu karst landscape.

CONCLUSIONS

The results of this study demonstrate that the phenomenon of Karst Rock Desertification (KRD) in the Gunung Sewu karst landscape of Tepus, Gunungkidul, is both measurable and visible using imagery used and field verification. Between 2019 and 2024, a significant shift occurred from non-degraded to potentially degraded zones, primarily driven by increasing anthropogenic pressures such as quarrying and tourism expansion.

While the Potential Rocky Desertification zone increased, more severe categories remained relatively stable or even decreased in area, indicating that early-stage degradation dominates the current landscape. This suggests an opportunity for timely intervention before conditions worsen. Field validation further supports the satellite-based findings, revealing that vegetation cover and soil depth are reliable indicators of desertification severity.

Ecologically, the increase in exposed bedrock and declining vegetation can trigger a chain reaction of soil instability, erosion, biodiversity loss, and ecological imbalance. Therefore, this study reinforces the need for targeted ecological restoration and sustainable land-use planning, especially in vulnerable karst environments.

This study primarily focused on exploring the application of Sentinel-2A imagery to assess karst rock desertification using a combination of vegetation indices (NDVI, FVC) and rock exposure indicators (NDRI, Fr). However, the analysis was limited to spatial and temporal pattern identification without extensively incorporating the underlying driving factors of desertification. Furthermore, the validation process was conducted independently of socio-ecological variables, which may influence the progression of degradation. Future research should aim to integrate socio-economic, climatic, and land-use data to provide a more comprehensive understanding of the causative mechanisms behind KRD and to enhance the predictive value of imager used based assessments.

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