



# Land Use Mapping Using Sentinel-2 Imagery and Volcanic Hazard Zonation for Sustainable Disaster Risk Reduction in the Mount Bromo Area, Probolinggo Regency, Indonesia

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**Abstract:** This study examines the spatial relationship between land use/land cover (LULC), volcanic hazard zones, and soil conditions in the Mount Bromo area of Probolinggo Regency, East Java, Indonesia. It aims to identify dominant LULC classes, quantify their overlap with volcanic hazard zones, and provide a spatial basis for risk-sensitive land-use planning. Sentinel-2 imagery was classified into four classes: vegetation, open land, agricultural land, and built-up area, and the results were evaluated using a confusion matrix. The classification achieved an overall accuracy of 81.97% and a kappa coefficient of 0.82, indicating reliable performance for regional-scale analysis. Agricultural land was the dominant class, covering 121,477.01 ha or 71.62% of the study area. Volcanic hazard zonation shows that 5,439.86 ha or 3.21% of Probolinggo Regency falls within Mount Bromo's low-, moderate-, and high-hazard zones, including 941.66 ha or 0.56% in the high-hazard zone. Overlay analysis revealed that 212.39 ha of agricultural land and 16.33 ha of built-up area are located in the high-hazard zone, while 389.45 ha of agricultural land and 9.34 ha of built-up area remain in the moderate-hazard zone. Hazardous zones also spatially coincide with Mollic Andosols, indicating that volcanic risk overlaps with productive soils. These findings show that productive land and settlement-related land use are still not fully aligned with volcanic hazard conditions, highlighting the need for risk-sensitive spatial planning and adaptive land management.

**Keywords:** Land use/land cover; Mount Bromo; Risk-sensitive spatial planning; Sentinel-2 imagery; Volcanic hazard zonation

## Introduction

Mount Bromo, part of the Bromo-Tengger volcanic complex in East Java, Indonesia, is an active volcano characterized by recurrent eruptive activity that generates ashfall, lapilli, and volcanic gases. These eruptive processes affect the surrounding landscape by reducing air quality, disturbing agricultural activities, altering soil conditions, and exposing settlements and infrastructure to volcanic hazards. In Probolinggo Regency, where human activities remain closely connected to the volcanic landscape, understanding the spatial relationship between hazard zones and existing land use is essential for improving disaster mitigation

and supporting sustainable land management (Bonadonna et al., 2021; Orynbaikyzy et al., 2025).

At the same time, the Mount Bromo area continues to experience pressure from agricultural expansion, population growth, and tourism-related development. These processes have reshaped land use across the volcanic landscape and increased the likelihood that productive land and settlement-related activities intersect with hazardous areas. In regions where livelihoods depend strongly on land-based activities, the distribution of agricultural land, vegetation, open land, and built-up areas directly influences the degree of exposure to volcanic hazards. For this reason, identifying the current land use/land cover (LULC)

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pattern in relation to Mount Bromo's hazard zonation is necessary to show the measurable extent of spatial exposure and to provide an evidence base for risk-sensitive land-use planning (Indarto & Hakim, 2021; Mandala et al., 2023).

Remote sensing and geographic information systems (GIS) provide an effective approach for analyzing land conditions in complex volcanic environments. In particular, Sentinel-2 imagery offers an important opportunity for current LULC mapping because of its 10 m spatial resolution and relatively frequent temporal coverage, which are suitable for identifying dominant land-cover classes at the regional scale. Although Sentinel-2 is not designed to distinguish all micro-scale objects in highly heterogeneous terrain, it remains a reliable source for mapping the main land-cover pattern and supporting spatial overlay analysis in mountainous volcanic regions (Chen et al., 2022; Kumari & Karthikeyan, 2023).

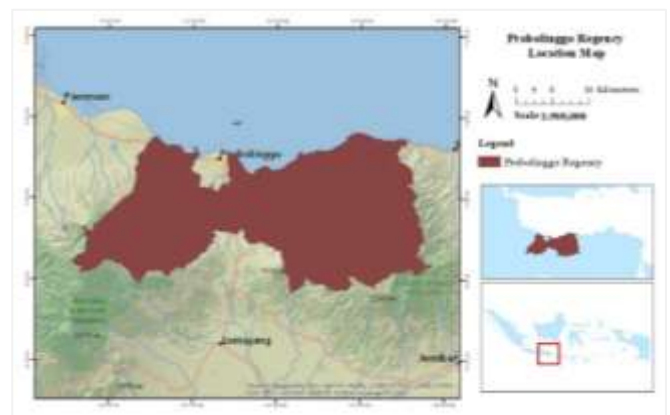
However, volcanic disaster risk is not determined only by the location of official hazard zones. Environmental characteristics, especially soil conditions, also influence land capability, agricultural suitability, infiltration, erosion sensitivity, and landscape response to disturbance. In the Mount Bromo region, volcanic soils contribute to high agricultural productivity while at the same time reflecting environmental vulnerability. This creates a land-management challenge, because areas that are valuable for cultivation may also be exposed to significant volcanic risk. Previous studies have discussed LULC change, volcanic hazards, and soil-related environmental characteristics separately, but integrated spatial assessment of current LULC, volcanic hazard zonation, and soil conditions in the Mount Bromo area of Probolinggo Regency remains limited. This study addresses that gap by linking these three components within a single GIS-based framework (Leenaars et al., 2020; Zairina et al., 2024).

Accordingly, the novelty of this study lies in its integrated spatial assessment of current LULC distribution, volcanic hazard zonation, and soil characteristics in the Mount Bromo area using Sentinel-2 imagery and GIS-based overlay analysis. Rather than examining land cover, hazard, or soil conditions independently, this study quantifies how agricultural land, built-up area, and other land-cover classes overlap with Mount Bromo's hazard zones and how these hazardous areas correspond to the distribution of volcanic soils. Therefore, this study aims to map the current LULC distribution, analyze its spatial overlap with volcanic hazard zones, and examine the associated soil conditions in Probolinggo Regency. The results are expected to contribute to risk-sensitive spatial planning, adaptive land management, and disaster-risk reduction in volcanic landscapes.

## Method

### Study Area

This study was conducted in the Mount Bromo area of Probolinggo Regency, East Java, Indonesia, as shown in Figure 1. Probolinggo Regency covers a total area of 169,616.65 ha and represents part of an active volcanic landscape within the Bromo–Tengger volcanic system. The study area was selected because agricultural land, settlements, open land, and natural vegetation coexist under different levels of volcanic hazard exposure, making it suitable for examining the spatial relationship among current land use/land cover (LULC), soil characteristics, and volcanic hazard zonation (Suprayogo et al., 2020; Toulrier et al., 2019).



**Figure 1.** Geographical location of the study area within Probolinggo Regency, East Java, Indonesia

### Data Sources and Acquisition

This study used a multi-source spatial dataset consisting of Sentinel-2 imagery, administrative boundary data, soil data, a digital elevation model (DEM), and Mount Bromo volcanic hazard-zonation data. The Sentinel-2 image used for LULC mapping was acquired on 23 September 2025 from the Copernicus data source and employed the Level-2A product, which provides surface reflectance data suitable for land-cover analysis. Administrative boundary data from the Probolinggo Regency Government were used to delineate the study area. Soil data were obtained from the Ina-Geoportal platform, while volcanic hazard-zonation data were obtained from the InaRISK platform based on the latest available Mount Bromo hazard information accessed during the study period. In addition, SRTM DEM data were used to support terrain interpretation and map preparation. The use of these multiple spatial datasets enabled an integrated analysis of land-cover conditions, environmental characteristics, and volcanic hazard exposure in Probolinggo Regency (Chandra et al., 2025; Nasiri et al., 2022).

### *Satellite Image Preprocessing*

Prior to classification, the Sentinel-2 imagery was preprocessed in ArcGIS to improve analytical consistency and thematic separability. The preprocessing steps included mosaicking, clipping the imagery to the administrative boundary of the study area, resampling, and band stacking. Because the image product used in this study was Sentinel-2 Level-2A, no additional atmospheric correction was applied. Instead, an image scene with minimal cloud cover was selected to reduce cloud-related interference during image interpretation and classification. To improve land-cover discrimination, spectral information from Bands 2, 3, and 4 was combined with the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Built-up Index (NDBI). These variables were used to strengthen the separation of vegetation, agricultural land, open land, and built-up area in the Mount Bromo landscape (Arfa & Minaei, 2024; Rumora et al., 2020).

### *Land Use/Land Cover Classification*

The preprocessed Sentinel-2 imagery was classified into four major LULC classes: vegetation, open land, agricultural land, and built-up area. These classes were selected to represent the dominant land-cover patterns in the study area and to reflect the main landscape units relevant to volcanic hazard exposure. Supervised classification was conducted in ArcGIS using the Maximum Likelihood algorithm. Training samples for each class were prepared through a combination of visual interpretation, cross-checking with Google Earth imagery, and limited field verification at selected locations. The resulting classification map was used as the main thematic layer for examining the spatial distribution of LULC in relation to hazard zones and soil classes. This approach is appropriate for identifying dominant land-cover units in complex volcanic environments while maintaining methodological transparency and reproducibility (Ghayour et al., 2021; Junianto et al., 2023).

### *Accuracy Assessment*

The classification result was evaluated using a confusion matrix, from which producer's accuracy, user's accuracy, overall accuracy, and the kappa coefficient were derived. These indicators were used to quantify the level of agreement between the classified image and the reference data and to ensure that the resulting LULC map was sufficiently reliable for subsequent spatial overlay analysis. Reference data for validation were compiled from visual interpretation, Google Earth image checks, and limited field observations. In remote sensing-based land-cover studies, confusion-matrix metrics remain the standard

approach for assessing classification quality and supporting the scientific validity of thematic mapping outputs (Mappatoba et al., 2025; Nurhasanah et al., 2023).

### *Soil Data Processing*

The soil dataset obtained from Ina-Geoportal was processed to identify the major soil classes distributed across the study area, including Eutric Fluvisols, Eutric Regosols, Vertic Luvisols, Mollic Andosols, and Ochric Andosols. The soil layer was standardized and spatially aligned with the other thematic datasets to enable further overlay analysis. Soil information was included because soil properties in volcanic regions influence land capability, agricultural suitability, infiltration characteristics, erosion sensitivity, and environmental vulnerability. In the Mount Bromo area, volcanic soils play a dual role by supporting agricultural productivity while also reflecting susceptibility to disturbance under volcanic and climatic stress. Therefore, soil data were treated as an important component of the integrated disaster-risk assessment (Suprayogo et al., 2020; Widjajanto et al., 2025).

### *Hazard Zonation Mapping*

Hazard zonation mapping was conducted using Mount Bromo volcanic hazard data obtained from the InaRISK platform. For analytical consistency, the study area was classified into three main hazard levels: low, moderate, and high hazard, together with the non-hazard or safe zone outside the mapped volcanic hazard area. This layer was used to distinguish the relative spatial extent of volcanic threat across Probolinggo Regency and to identify which parts of the landscape are more exposed to eruption-related processes. Hazard zonation provides an essential spatial basis for disaster-risk analysis because it translates volcanic processes into operational categories that can be compared with existing land use and environmental conditions. In this study, the hazard-zonation map served as the primary exposure layer for evaluating how current land-cover patterns and soil types are distributed across different levels of volcanic risk (Anggana et al., 2024; Lindsay et al., 2023).

### *Spatial Integration and Disaster Risk Mapping*

After all thematic layers were standardized into a common coordinate system, namely WGS 84 / UTM Zone 49S, and adjusted to the same spatial extent, spatial integration was carried out using GIS-based overlay analysis in ArcGIS. The LULC map, soil map, and hazard-zonation map were combined primarily using the Intersect tool to generate new spatial units representing the overlap among land-cover classes, soil types, and hazard levels. Reclassification was applied

where necessary to standardize thematic categories before overlay processing. Through this procedure, it was possible to identify which land-cover categories and soil classes are located within low-, moderate-, and high-hazard zones. The overlay result formed the basis for disaster-risk interpretation by showing how productive land, open land, vegetation, and built-up areas are spatially associated with volcanic exposure. Unlike the hazard-zonation subsection, this stage focused on the technical integration of multiple datasets rather than the classification of hazard zones alone (Reyes-Hardy et al., 2021; Topuz & Deniz, 2023).

*Statistical and Spatial Analysis*

Following the spatial integration process, statistical and spatial analyses were conducted to calculate area extent, percentage of total area, and the distribution of each thematic class and overlay result. Area-based calculations were generated automatically in GIS in hectare units and then summarized in tabular form using Microsoft Excel. These calculations were used to quantify the proportion of each LULC class, the extent of each hazard zone, the distribution of soil types, and the magnitude of overlap among these layers. The outputs provided the quantitative basis for interpreting current land-use exposure and environmental sensitivity in the Mount Bromo area. The combined use of spatial overlay and descriptive statistics is widely applied in geospatial risk assessment because it supports clear comparison across categories and improves the policy relevance of the findings (Purwanto & Paiman, 2023; Reyes-Hardy et al., 2021).

*Workflow Overview*

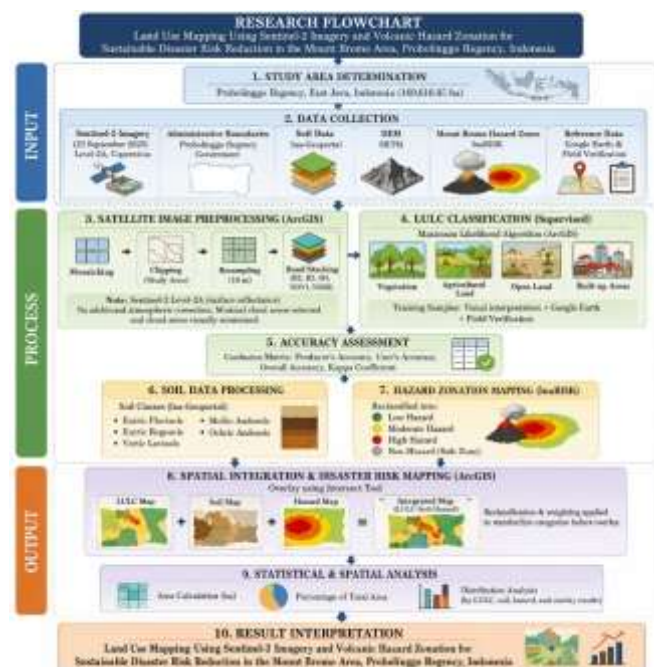


Figure 2. Research flow chart

The overall workflow of this study is summarized in Figure 2. The workflow consisted of study-area delineation, collection of Sentinel-2 imagery and supporting spatial datasets, image preprocessing through mosaicking, clipping, resampling, and band stacking, derivation of NDVI and NDBI, supervised LULC classification using the Maximum Likelihood algorithm, accuracy assessment using a confusion matrix, preparation of soil and hazard datasets, GIS-based spatial integration, and statistical interpretation of the resulting overlay outputs. The inclusion of a flowchart is intended to improve the clarity, transparency, and reproducibility of the research procedure, especially for readers who wish to understand the sequence of data processing and spatial analysis used in this study (Budiman et al., 2025; Chaves et al., 2023).

**Result and Discussion**

*Land Use and Land Cover (LULC) Classification and Accuracy Assessment*

The LULC classification for Probolinggo Regency in 2025 shows that agricultural land is the dominant land-cover class, covering 121,477.01 ha or 71.62% of the total mapped area (Table 1). Vegetation, open land, and built-up area occupy smaller proportions of the regency, indicating that the regional landscape remains strongly agrarian despite the presence of non-agricultural land uses. This pattern is also visible in Figure 3, where agricultural land forms the dominant spatial matrix across much of the study area. Such a distribution is consistent with previous studies in East Java reporting the persistence of agricultural land as a major land-use component, although local conversion to built-up land and other non-agricultural uses continues to occur in selected development corridors (Faoziyah et al., 2024; Mandala et al., 2023).

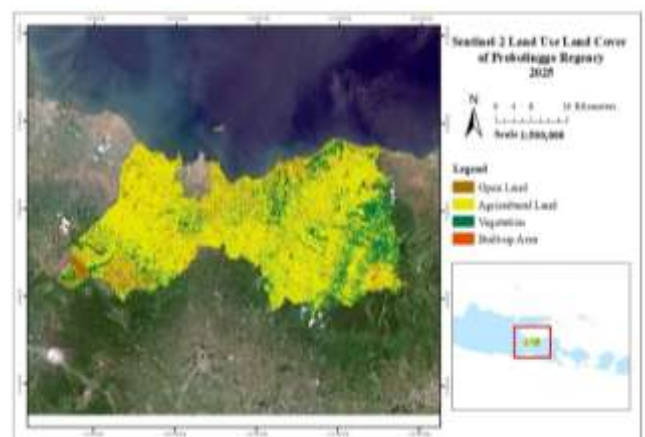


Figure 3. Spatial distribution of LULC classes in Probolinggo Regency, East Java, for the year 2025

The reliability of the classified map is supported by the accuracy assessment results, which indicate an overall accuracy of 81.97% and a kappa coefficient of 0.82. These values suggest strong agreement between the classified output and the reference data, confirming that the resulting LULC map is sufficiently reliable for subsequent spatial analysis. Following the reviewer’s comment, the confusion matrix and class-specific accuracy values were rechecked to correct any tabulation inconsistencies in Table 1, particularly the

repeated Producer’s Accuracy and User’s Accuracy values. The revised class-level accuracies are presented in the updated table and should be interpreted as the corrected basis for evaluating the thematic quality of each land-cover class. In methodological terms, this level of accuracy remains acceptable for regional-scale LULC mapping using Sentinel-2 imagery, especially for distinguishing dominant land-cover categories in complex landscapes (Rifai & Harintaka, 2024; Yuli Handoko et al., 2024).

**Table 1.** Land Use and Land Cover (LULC) Classification and Accuracy Assessment for 2025 In Probolinggo Regency

LULC classes	Area (ha)	Percentage (%)	Producer’s Accuracy (%)	User’s Accuracy (%)	Representation
Vegetation	32923.71	19.41	71.43	83.33	Very good
Open land	9102.96	5.37	80.00	66.67	
Agricultural land	121477.01	71.62	80.00	66.67	
Built-up area	6112.98	3.60	100.00	83.33	
Total	169616.65	100			
Overall Accuracy	81.97%				
Kappa coefficient	0.82				

*Volcanic Hazard Zonation of Mount Bromo*

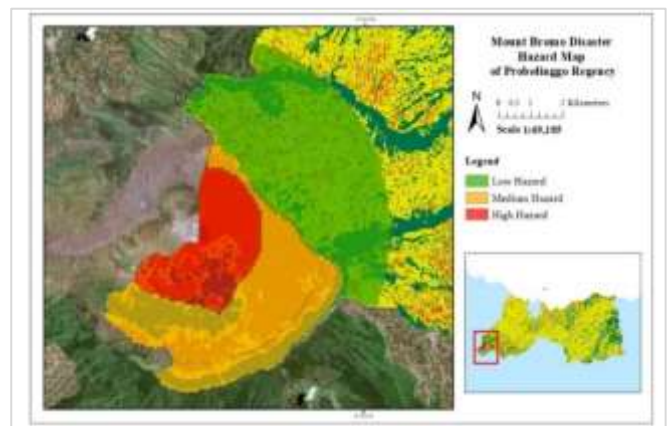
The volcanic hazard zonation of Mount Bromo reveals a clear spatial pattern, classifying the affected area into three risk categories: low, moderate, and high hazard (Figure 4). Based on Table 2, the high-hazard zone is concentrated in areas directly adjacent to the active crater, the moderate-hazard zone forms a transitional belt surrounding it, and the low-hazard zone extends across the peripheral areas. This pattern is consistent with previous volcanic hazard studies, which generally show a decline in hazard intensity with increasing distance from the crater and highlight the influence of topography and eruption-related processes on hazard distribution (Ibrahim et al., 2024; Thakur et al., 2024).

**Table 2.** Analysis of Affected Area by Hazard Level in Probolinggo Regency

Hazard level	Area (ha)	Percentage of total area (%)
Low hazard	2563.51	1.51%
Moderate hazard	1934.68	1.14%
High hazard	941.66	0.56%
Safe zone	164176.78	96.79%
Total	169616.65	100%

Quantitatively, Table 2 indicates that the low-hazard zone covers the largest area, amounting to 2,563.51 ha (1.51%), followed by the moderate-hazard zone with 1,934.68 ha (1.14%), and the high-hazard zone with 941.66 ha (0.56%), giving a total affected area of 5,439.86 ha (3.21%). Although the high-hazard zone occupies the smallest proportion of land, it represents the most critical level of threat because of its immediate proximity to the active eruptive center. This finding supports earlier research showing that proximal crater areas typically constitute the most hazardous zones,

while surrounding transitional and peripheral zones reflect progressively lower levels of exposure depending on the hazard model and spatial data used (Praveen & Kunampalli, 2024; Thakur et al., 2024).



**Figure 4.** Spatial distribution of volcanic disaster hazard zones for Mount Bromo, Probolinggo Regency, categorized into low, moderate, and high-risk levels

*Spatial Intersection between LULC and Hazard Zones*

The spatial overlay between land use/land cover (LULC) classes and hazard levels in Table 3 shows that agricultural land represents the largest LULC category within the hazard zones, covering 2,157.58 ha, although most of this area is located within the low-hazard zone (1,555.74 ha). In contrast, open land exhibits the greatest concentration within the moderate- and high-hazard classes, covering 943.30 ha and 533.66 ha, respectively, which indicates a stronger spatial association with the more hazardous zones. Vegetation is also distributed across all hazard levels, while built-up land occupies a relatively small total area (94.22 ha) but remains present in both moderate- and high-hazard zones. These

patterns suggest that human land use, particularly productive land and settlement-related areas, continues to intersect with zones of potential volcanic hazard, reflecting a meaningful linkage between land utilization and hazard exposure in the study area (Gholami et al., 2023; Li et al., 2024).

From a spatial planning perspective, the presence of agricultural land and built-up areas within moderate- and high-hazard zones indicates that disaster mitigation considerations may not yet be fully integrated into land allocation and development control. Although agricultural land is predominantly situated in the low-hazard class, its extension into hazardous zones, together with the occurrence of settlement areas in high-

hazard locations, remains important because it may increase the risk of economic disruption, damage to productive assets, and potential loss of life during future eruptions. Therefore, Table 3 highlights not only the uneven distribution of LULC across hazard classes but also the continuing need for risk-sensitive zoning, stronger settlement control in exposed areas, and adaptive land management for productive landscapes located near hazardous zones. This interpretation is consistent with earlier studies emphasizing the value of spatial overlay analysis for informing hazard-aware land use planning and targeted mitigation in exposed landscapes (Masiero et al., 2024; Seeger et al., 2024).

**Table 3.** Spatial Intersection Between Land Use/Land Cover (LULC) Classes and Hazard Levels

LULC	Low hazard (ha)	Moderate hazard (ha)	High hazard (ha)	Safe zone (ha)	Total area (ha)
Vegetation	649.81	592.09	178.92	31502.89	32923.71
Open land	289.23	943.30	533.66	7335.72	9102.95
Agricultural land	1555.74	389.45	212.39	119319.42	121477.00
Built-up area	68.54	9.34	16.33	6018.75	6112.97
Total	2563.51	1934.68	941.66	164176.78	169616.65

*Soil Classification and Its Spatial Characteristics*

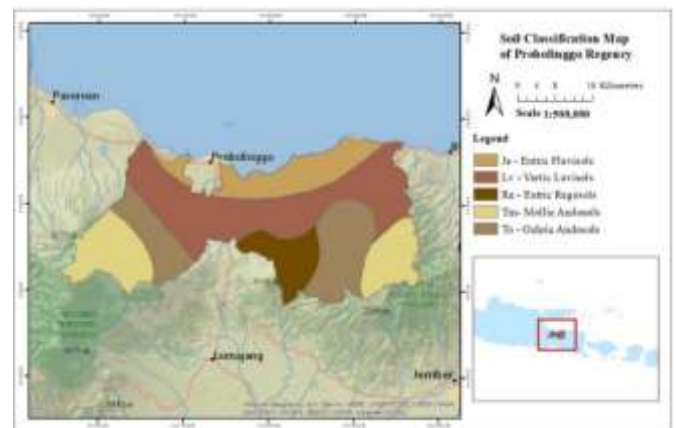
The soil classification results indicate that Vertic Luvisols are the dominant soil class in Probolinggo Regency, followed by Ochric Andosols and Mollic Andosols (Table 4). This composition reflects the strong influence of volcanic parent material and associated soil-forming processes on the regional landscape. The relatively large proportion of Andosol-related soils also highlights the agricultural importance of the area, as volcanic soils are often associated with good fertility and productive land use. At the same time, these soils contribute to a spatially heterogeneous land system in which productivity and environmental sensitivity coexist (Abdullah et al., 2024; Suprayogo et al., 2020).

**Table 4.** Soil Classifications in Probolinggo Regency

Soil classification	Area (ha)	Percentage of total area (%)
Eutric fluvisols	23868.03	14.07%
Vertic luvisols	60989.29	35.96%
Eutric regosols	14220.66	8.38%
Mollic andosols	33627.41	19.83%
Ochric andosols	36911.24	21.76%
Total	169616.65	100.00%

The soil distribution shown in Figure 5 also provides an important context for interpreting land-use suitability and environmental vulnerability. In volcanic landscapes, soil properties affect infiltration, erosion sensitivity, land capability, and resilience under disturbance. Therefore, the mapped soil classes are not only relevant for agricultural evaluation but also for understanding how physical environmental characteristics interact with hazard exposure. In this sense, the soil map complements the LULC and hazard

analyses by adding an environmental dimension to the assessment of disaster risk and land-management challenges in Probolinggo Regency (Leenaars et al., 2020; Zairina et al., 2024).



**Figure 5.** Spatial distribution of soil types in Probolinggo Regency based on international soil classification standards

*Soil Distribution Across Hazard Zones*

The distribution of soil types across hazard zones indicates that Mollic Andosols are the only soil group present within areas classified as hazardous, while Eutric Fluvisols, Vertic Luvisols, Eutric Regosols, and Ochric Andosols are absent. This pattern highlights a strong spatial association between volcanic soils and hazard-prone environments, particularly in landscapes shaped by volcanic deposits, steep slopes, and active geomorphological processes. In volcanic regions, the dominance of Andosols in hazardous areas can be attributed to their formation on ash-derived parent

materials and their interaction with slope dynamics and hydrological processes, which together increase susceptibility to erosion and shallow landslides (Marin et al., 2024; Sisay et al., 2024).

This finding also reveals a critical trade-off between agricultural productivity and disaster risk, as volcanic soils are widely recognized for their high fertility yet are concentrated in moderate- to high-hazard zones. Consequently, areas with the greatest agricultural

potential are simultaneously those most vulnerable to environmental disturbances. This duality underscores the importance of integrating soil characteristics into hazard mitigation and land-use planning. Effective strategies such as soil conservation, slope stabilization, and sustainable land management are therefore essential to maintain soil productivity while reducing disaster risk in volcanic landscapes (Chedid et al., 2023; Sisay et al., 2024).

**Table 5.** Spatial Distribution of Soil Classifications across Hazard Zones

Soil classification	Low hazard (ha)	Moderate hazard (ha)	High hazard (ha)	Safe zone (ha)	Total area (ha)
Eutric fluvisols	0	0	0	23868.03	23868.03
Vertic luvisols	0	0	0	60989.29	60989.29
Eutric regosols	0	0	0	14220.66	14220.66
Mollic andosols	2563.51	1934.68	941.66	28187.54	33627.41
Ochric andosols	0	0	0	36911.24	36911.24
Total	2563.51	1934.68	941.66	164176.78	169616.65

*Implications for Disaster Risk Mitigation and Regional Planning*

The spatial intersection of land use/land cover, volcanic hazard zones, and soil conditions indicates that disaster-risk mitigation in the Mount Bromo area should be translated into operational land-management and settlement-control measures. The overlay results show that 16.33 ha of built-up area are located in the high-hazard zone and 9.34 ha in the moderate-hazard zone, while agricultural land covers 212.39 ha in the high-hazard zone and 389.45 ha in the moderate-hazard zone. These figures confirm that both settlement-related land use and productive land remain exposed to volcanic hazards. Therefore, the high-hazard zone should be treated as a strict control area, where no new permanent settlements, tourism accommodation, public-service buildings, or strategic infrastructure should be permitted. Existing built-up areas within this zone should be prioritized for phased relocation planning, restriction of building expansion, installation of hazard signboards, and the designation of fixed evacuation routes and assembly points. In areas where relocation cannot yet be implemented, local disaster preparedness should be strengthened through community-based early warning systems, routine evacuation drills, and the provision of emergency communication points. By contrast, the moderate-hazard zone should be managed as a conditional-use area, where any new development must first pass hazard-based site screening and demonstrate access to evacuation routes and emergency procedures (Bachri et al., 2024; Bonadonna et al., 2021).

The results also indicate that agricultural land remains exposed in Mount Bromo’s hazardous zones, particularly 212.39 ha in the high-hazard zone and 389.45 ha in the moderate-hazard zone. This condition requires adaptive agricultural management rather than conventional land-use control alone. Recommended

measures include the use of short-cycle or ash-tolerant crops, protected storage for seeds and fertilizers, temporary crop protection where feasible, and field-cleaning protocols after ashfall events. In addition, open land in the moderate- and high-hazard zones should be stabilized through revegetation and agroforestry-based buffers to reduce erosion and support faster post-eruption recovery. The soil overlay further shows that the hazardous zones spatially coincide with Mollic Andosols, indicating that areas exposed to volcanic risk are also associated with agriculturally productive volcanic soils. This means that mitigation in the Mount Bromo area should prioritize two concrete targets: exposed built-up land in the high-hazard zone for settlement control and emergency preparedness, and exposed agricultural land in the moderate- and high-hazard zones for adaptive farming and sustainable land management (Saputra et al., 2022; Sari et al., 2023).

**Conclusion**

This study confirms that land use in the Mount Bromo area of Probolinggo Regency still overlaps with volcanic hazard zones. The Sentinel-2 classification result was reliable, with an overall accuracy of 81.97% and a kappa coefficient of 0.82. Agricultural land remains the dominant land-cover class, covering 121,477.01 ha (71.62%), while 5,439.86 ha (3.21%) of the regency falls within volcanic hazard zones, including 941.66 ha (0.56%) in the high-hazard zone. Overlay analysis shows that 212.39 ha of agricultural land and 16.33 ha of built-up area are still located in the high-hazard zone, indicating that productive and settlement-related land uses are not yet fully aligned with hazard conditions. The spatial coincidence between hazard zones and Mollic Andosols further highlights the challenge of managing productive but hazard-prone

land. Therefore, the high-hazard zone should be strictly controlled for permanent development and prioritized for relocation, evacuation planning, and community-based early warning systems, while agricultural land in the moderate- and high-hazard zones should be directed toward adaptive farming and post-eruption land management. Overall, this study provides a clear spatial basis for risk-sensitive planning in the Mount Bromo area.

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#### Author Contributions

Conceptualization, D.F.K. and S.; methodology, D.F.K., S., and F.R.S.; validation, S. and F.R.S.; formal analysis, D.F.K. and S.; investigation, D.F.K., S., and F.R.S.; resources, S. and F.R.S.; data curation, D.F.K.; writing—original draft preparation, D.F.K.; writing—review and editing, S. and F.R.S.; visualization, D.F.K.; supervision, S. and F.R.S.; project administration, D.F.K. All authors have read and agreed to the published version of the manuscript.

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#### Conflicts of Interest

The authors declare no conflict of interest.

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