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Evaluation of Post - Volcanic Land Suitability in the Mount Sinabung Area for Red Chili (*Capsicum annuum* L.) Cultivation Using the FAO Land Evaluation Approach, Naman Teran District, Karo Regency, Indonesia

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ABSTRACT: This study was designed to assess the land suitability level for red chili (*Capsicum annuum* L.) cultivation on areas impacted by the eruption of Mount Sinabung in Naman Teran District, Karo Regency Indonesia. The research was carried out from November 2025 to February 2026 using a survey - based approach combined with spatial and descriptive analyses. The overlay of soil type, elevation, and slope maps generated 13 Land Map Units (LMUs), although eruption - affected zones were concentrated in two villages within a particular LMU. Land suitability was evaluated using a matching technique that compared land characteristics with crop growth requirements. The results indicate that both study sites are generally classified as not suitable (N), with nutrient retention and erosion hazard identified as the dominant limiting factors. However, several individual land characteristics remain within the S1- S3 suitability range. Although several individual parameters fall within S1 - S3 classes, the overall Land Suitability Index (LSI) remains low, reflecting the multiplicative interaction of limiting factors. Soil acidity can be partially improved through liming; however, nutrient retention remains a persistent constraint due to the inherent properties of volcanic ash-derived soils.Certain constraints, such as soil pH, can be mitigated through liming; however, low nutrient retention remains a critical limitation that is difficult to substantially improve.

KEYWORDS: land evaluation, red chili, volcanic eruption, soil fertility

INTRODUCTION

Karo Regency is one of the key horticultural production centers in Indonesia, particularly in North Sumatra, and is well known for red chili pepper cultivation. Naman Teran District possesses favorable agroecological conditions, with elevations ranging from 1,300 to 1,450 meters above sea level. However, the eruption of Mount Sinabung in recent years has significantly altered the physical and chemical properties of the soil, thereby affecting agricultural productivity in the region (Simanjuntak, C.M., Deni Elfiati, and Delvian, 2015; Sukarman, Mulyani, and Purwanto, 2020; Tarigan, 2015).

Land suitability evaluation is a crucial approach for determining the appropriateness of an area for specific commodity development. This approach generally involves matching land characteristics with crop growth requirements. In horticultural crops such as red chili peppers, key determining factors include soil reaction (pH), texture, water availability, and nutrient retention capacity (Weil and Brady, 2017; Pinatih, Kusmiyarti, and Susila, 2019; Zhiddiq, Badwi, and Haeril, 2021; Prayoga et al., 2021; Harahap et al., 2018).

In areas with undulating to steep topography, major limitations are commonly associated with low nutrient availability and a high risk of erosion. These constraints often result in land being classified as marginally suitable. In addition, changes in land morphology due to volcanic deposits further increase susceptibility to land degradation (Lal, 2015; Bouma, 2002; Fleige et al., 2016; Putri and Sasongko, 2023).

Soils derived from volcanic materials exhibit distinctive characteristics. On the one hand, they have the potential for high mineral content; on the other hand, they often face constraints such as low organic matter, soil acidity, and weak nutrient retention, particularly during the early post-eruption phase. Moreover, agricultural intensification without appropriate management can

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accelerate soil degradation, especially through declines in soil pH and organic matter content (Lal, 2015; Mutmainnah et al., 2021; Putri and Sasongko, 2023).

To date, studies evaluating land suitability in post-volcanic eruption areas—especially for red chili - remain limited. In addition, only a few studies explicitly differentiate between permanent (inherent) limiting factors and those that can be improved through land management interventions (Taani, Husban, and Farhan, 2020; Mujiyo et al., 2026; Sukarman, Mulyani, and Purwanto, 2018; Rossiter, 1996; Bouma, 2002; Lal, 2015; Sys et al., 1991; FAO, 1976). Despite the growing body of research on land suitability, studies focusing on post-volcanic environments remain limited, particularly for horticultural crops such as red chili. Moreover, previous studies have rarely integrated spatial analysis with a clear distinction between inherent and manageable limiting factors in dynamic soil systems.

This study contributes in three main aspects: (1) it advances land suitability evaluation in post-volcanic landscapes by focusing on soils affected by the eruption of Mount Sinabung, which are characterized by rapidly changing physicochemical properties; (2) it develops an integrated approach combining GIS-based Land Map Units (LMUs) with a matching method to assess both actual and potential land suitability; and (3) it provides a more refined classification of limiting factors by distinguishing between permanent (inherent) constraints and those that can be improved through land management interventions, thereby offering a more practical basis for adaptive land-use planning.

Based on this background, this study aims to evaluate land suitability for red chili cultivation in areas affected by the eruption of Mount Sinabung using a spatial analysis approach, with emphasis on both actual and potential land suitability.

RESEARCH METHODS

This study was conducted from November 2025 to February 2026. The research was carried out in Naman Teran District, Karo Regency, located at 02°50′– 03°19′ North Latitude and 97°55′–98°38′ East Longitude. The study area covers approximately 2,206.88 km² and lies at an elevation ranging from 0 to 1,400 meters above sea level.

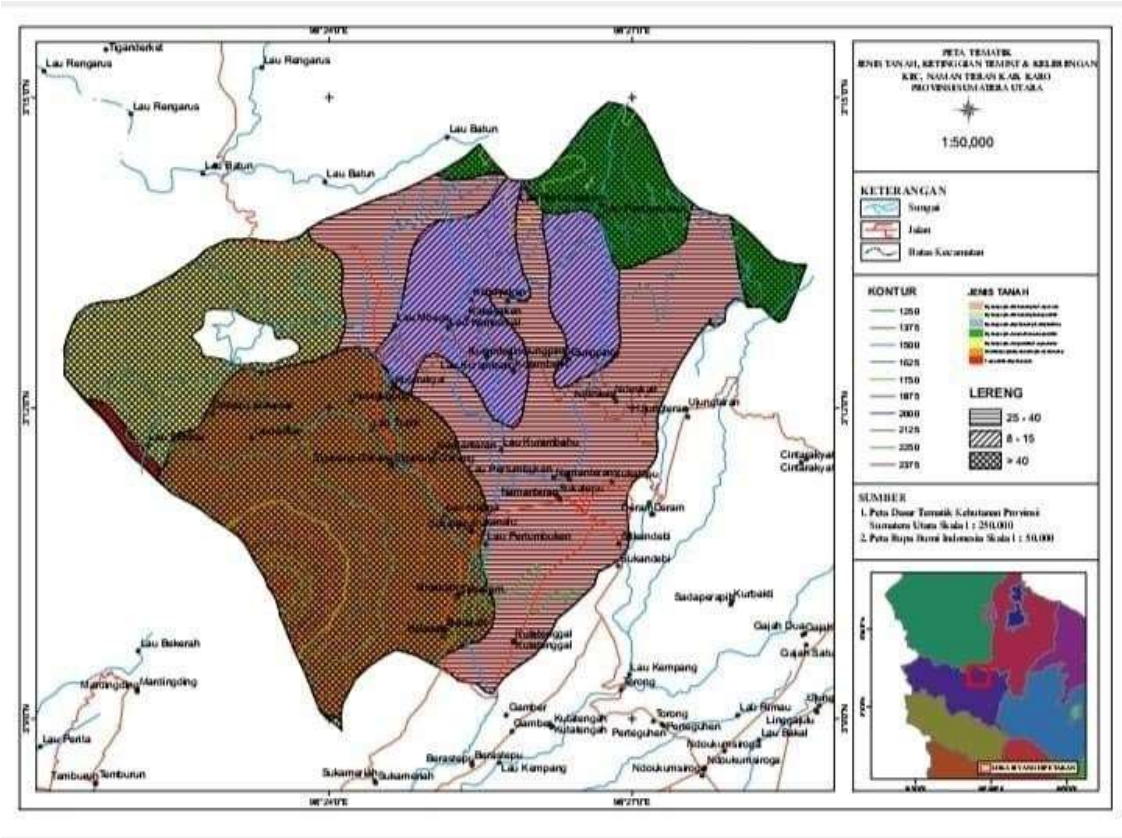

Figure 1. Land Map Units

This study employed a survey method combined with a descriptive approach and spatial analysis based on Land Map Units (LMUs). The LMUs were generated through the overlay of soil type, slope gradient, and elevation maps using ArcGIS software (Figure 1).

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The data used in this study consisted of:

- Primary data: soil physical and chemical properties obtained from field surveys and laboratory analyses, including pH, organic carbon, cation exchange capacity (CEC), and soil texture. Soil classification was conducted based on FAO (1976). The number of soil samples was determined using a purposive sampling method following established procedures from previous studies.
- Secondary data: climate data for the past 10 years obtained from the Meteorology, Climatology, and Geophysics Agency.

The relatively low index values confirm that nutrient retention and erosion hazard are dominant limiting factors, which significantly reduce overall land performance despite favorable climatic conditions.

Land suitability evaluation was conducted using a matching method based on the criteria of BBSDLP (2012). The parameters analyzed included temperature, water availability, nutrient retention, rooting media, and erosion hazard. The Food and Agriculture Organization (FAO, 1976) framework was selected due to its robustness, global acceptance, and systematic structure for evaluating land suitability across diverse agroecological conditions. This framework provides standardized criteria that enable the classification of land into suitability classes (S1, S2, S3, and N), thereby ensuring comparability and consistency with previous studies. In addition, the FAO approach is particularly suitable for assessing complex environments, including post- volcanic landscapes, where multiple biophysical factors interact dynamically.

The matching method was employed as the primary analytical approach because it allows for a direct comparison between land characteristics and crop growth requirements. This method is widely recognized for its practicality and reliability in land evaluation studies, as it facilitates the identification of limiting factors that constrain crop performance. Furthermore, the matching approach enables the differentiation between actual and potential land suitability, providing a more comprehensive basis for land-use planning and management.

By integrating the FAO framework with a matching-based evaluation and GIS- derived Land Map Units (LMUs), this study offers a structured and spatially explicit assessment of land suitability. This combination enhances the accuracy of suitability classification while supporting more targeted and adaptive land management strategies in post-eruption agroecosystems.

RESULTS AND DISCUSSION

Although several individual parameters fall within the S1-S3 suitability classes, the overall land suitability classification for both LMUs is categorized as not suitable (N), primarily due to the dominance of limiting factors related to nutrient retention and erosion hazard.

Climate Data

Climate data for the last 10 years (2015-2025) was obtained from the Meteorology, Climatology, and Geophysics Agency, Sampali Climatology Station Unit, Deli Serdang. This includes: Average monthly rainfall, air temperature, and humidity from the nearest observation post/station, the Parapat Observation Station in Karo Regency, which is considered representative of climate data in Namanteran District. The climate data obtained using the following averages:

a. Average annual air temperature: 20.1°C
b. Average rainfall: 2827 mm/year
c. Average annual humidity: 87.8%/year
d. Climate type (Oldeman: B (Wet Month)

The analysis results indicate that the agro-climatic conditions of the study area are relatively suitable for horticultural crop development, based on optimal temperature, rainfall, and humidity. These factors play an important role in plant physiological processes, such as photosynthesis, respiration, and yield formation. However, agro-climatic suitability does not always align with overall land suitability, as edaphic factors (soil) are often the main limitation in agricultural production systems (Weil, R.R., and N.C. Brady, 2017; Lal, 2015; Bouma, 2002; Mujiyo et al., 2020).

Land Suitability Evaluation

The overall suitability index was calculated using a multiplicative parametric model, which accounts for the interaction among limiting factors. This approach allows for a more quantitative and integrative assessment compared to the conventional matching method. Based on the matching results, the following evaluation results were obtained for the actual and potential land suitability classes for Red Chili Peppers (*Capsicum annuum* L.) in Sigarang-garang and Sukanalu Villages (Table 1):

Mechanisms of Low Nutrient Retention in Post-Volcanic Soils

The limited nutrient retention identified in the study area is closely related to the intrinsic properties of volcanic ash-derived soils, particularly Andisols. These soils are commonly dominated by short-range-order minerals, such as allophane and imogolite, which play a crucial role in determining their chemical characteristics. A primary factor contributing to low nutrient retention is the reduced effective Cation Exchange Capacity (CEC) under acidic soil conditions. In post-eruption settings, soils generally exhibit low

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pH levels, which decrease the number of negatively charged sites required for nutrient adsorption. Consequently, essential base cations, including Ca^{2+}, Mg^{2+}, and K^{+}, are more susceptible to leaching, thereby diminishing overall soil fertility.

Moreover, acidic environments enhance the solubility of aluminum (Al^{3+}) and iron (Fe^{3+}), which significantly contribute to nutrient fixation processes. Elevated levels of Al and Fe oxides can immobilize phosphorus (P) by forming insoluble compounds through phosphorus fixation, thus reducing its availability for plant uptake. This process is particularly evident in volcanic soils, where amorphous minerals exhibit strong affinity for phosphate ions.

In addition, the predominance of variable charge surfaces in Andisols makes their CEC highly dependent on soil pH. Under acidic conditions, the reduction in negative surface charge further constrains the soil's ability to retain nutrients. Although the application of organic matter can partially enhance CEC and nutrient retention, such improvements are often insufficient to counterbalance the inherent mineralogical limitations of volcanic soils. In summary, the combined effects of low soil pH, variable charge behavior, and intensive Al/Fe-driven nutrient fixation account for the persistently low nutrient retention observed in the study area. These findings reinforce previous research suggesting that, despite their favorable physical attributes, volcanic soils are constrained by chemical limitations that pose significant challenges to sustainable agricultural development.

The observed low nutrient retention in the Sinabung-affected soils is consistent with findings in volcanic ash soils in Japan and the Philippines, where allophanic clays exhibit strong phosphorus fixation and pH-dependent CEC (Nanzyo, 2002). However, compared to more stabilized Andisols in long-established volcanic landscapes, the study area shows relatively lower base saturation, indicating that post-eruption soil systems may experience more severe nutrient limitations during early pedogenic stages.

Table 1. The Actual and Potential Land Suitability Classes for Red Chili Peppers (*Capsicum annuum* L.)

Land Characteristics	**Sigarang-garang Values**	**Land Suitability Class (Actual)**	**Land Suitability Class (Potential)**	**Sukanalu Values**	**Land Suitability Class (Actual)**	**Land Suitability Class (Potential)**
Temperature (tc)						
Mean temperature (°C)	20,1	S1	S1	20,1	S1	S1
Water Availability (wa) Rainfall (mm)	707	S1	S1	707	S1	S1
Air humidity (%)	87,8	S2	S2	87,8	S2	S2
Oxygen Availability (oa) Drainage	Well-drained	S1	S1	Well-drained	S1	S1
Rooting Medium (rc)						
Soil texture	Sandy	S1	S1	Sandy	N	N
Coarse fragments (%)	< 15	S1	S1	< 15	S1	S1
Soil depth (cm)	101	S1	S1	100	S1	S1
Nutrient Retention (nr)						
Cation exchange capacity (CEC) (cmol(+)/kg)	10,33	S2	S2	11,03	S1	S1
Base saturation (%)	14.81	S3	S3	25,67	S2	S2
Soil pH (H_2O)	4,37	S3	S3	5,31	S2	S2
Organic carbon (%) **Toxicity (xc)**	1,9	S1	S1	0,47	S1	S1
Salinity (dS/m)	0,4714	S1	S1	0,1823	S1	S1
Sodicity (xn) Exchangeable sodium percentage (ESP) (%)	2,13	S3	S3	0,72	S3	S3
Erosion Hazard (eh)						
Slope (%)	>40	N	N	>40	N	N
Erosion risk	Moderate	S2	S2	Moderate	S2	S2
Flood Hazard (fh)						

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Flooding/ponding **Land Preparation (lp)**	F0	S1	S1	F0	S1	S1
Surface rock fragments (%)	5-15	S2	S2	15-40	S3	S3
Rock outcrops (%)	5 -15	S2	S2	15-40	N	N

Based on field survey observations, climate data, and soil analyses conducted at a depth of 0–30 cm, land characteristic data were obtained for a single Land Map Unit (LMU), although two villages - Sigarang-garang and Sukanalu - were affected by the eruption of Mount Sinabung.

The analysis results indicate that the study area has agroclimatic conditions characterized by an average temperature of 20.1°C, high rainfall, and relative humidity reaching 87.8%, which generally support the growth of horticultural crops (Weil and Brady, 2017; Pinatih et al., 2019; FAO, 1976; Sukarman et al., 2020). Volcanic soils typically exhibit favorable physical properties; however, they often face chemical constraints, particularly related to nutrient retention and soil acidity (Shoji et al., 1994; Nanzyo, 2002; Simanjuntak, C.M., Deni Elfiati, and Delvian, 2015; Tarigan, 2015).

However, the results of the land suitability evaluation show that:

- LMU 1 (Sigarang-garang Village): This unit is classified as not suitable (N), with nutrient retention (nr) and erosion hazard (eh) identified as the primary limiting factors. Low cation exchange capacity and base saturation indicate limited nutrient availability in the soil.
- LMU 2 (Sukanalu Village): This unit is also classified as not suitable (N), with similar primary constraints, along with soil texture that is less favorable for root development.

Land improvement measures, such as liming and the application of organic matter, can improve soil pH and cation exchange capacity. However, these interventions tend to provide only partial improvements and are insufficient to overcome inherent limitations, particularly those related to soil texture and the fundamental characteristics of nutrient retention.

NOVELTY. This study differs from previous research in that it possesses scientific novelty in the following aspects:

Bridging the Gap in Post-Volcanic Land Suitability Studies. This study addresses a critical deficiency in land suitability research by examining horticultural development within post-volcanic environments impacted by the eruption of Mount Sinabung. In contrast to earlier works that largely focus on relatively stable agroecosystems, this research expands the analytical scope of land evaluation under highly dynamic, disturbance-induced soil conditions, with specific emphasis on red chili (*Capsicum annuum* L.).

1. Integrative Framework of Spatial Analysis and Matching-Based Evaluation. The study develops a comprehensive analytical framework that integrates GIS- derived Land Mapping Units (LMU/SPL) with parametric matching techniques to evaluate both actual and potential land suitability concurrently. This integrated approach offers a more robust and decision-oriented assessment compared to conventional methods that rely on a single-state evaluation.
2. Advanced Delineation of Limiting Factors for Precision Management. A major contribution of this research is the systematic classification of limiting factors into inherent (permanent) and manageable (modifiable) categories. By clearly separating constraints such as nutrient retention from improvable attributes like soil pH and erosion, this study facilitates more targeted, efficient, and economically viable land management interventions beyond generalized suitability assessments.
3. Formulation of Adaptive Land Management for Post-Volcanic Systems. This research formulates a context-driven adaptive land management strategy by integrating soil amelioration practices (liming and organic amendments) with soil conservation measures. The proposed model not only improves land productivity but also strengthens the resilience and long-term sustainability of agroecosystems recovering from volcanic disturbances.

RECOMMENDATIONS

a) Further research is needed on volcanic soil amelioration technologies to more effectively improve nutrient retention. But, although soil amelioration practices such as liming and organic matter incorporation can enhance selected chemical properties, their effectiveness remains limited in overcoming structurally constrained factors, particularly those related to mineralogical control of nutrient retention in volcanic soils.

b) Comparative studies among horticultural commodities are recommended to identify crops that are more adaptive to post-eruption land conditions.

c) The development of machine learning-or remote sensing-based land evaluation models is recommended to improve the accuracy of land suitability mapping.

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CONCLUSION

Overall, land suitability for red chili cultivation in the study area is classified as not suitable (N), despite the presence of several moderately suitable characteristics (S1– S3). This indicates that land performance is primarily constrained by dominant limiting factors rather than individual parameter suitability.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE (AI)

The author declares that artificial intelligence (AI) was used in a limited capacity to improve language quality and clarity. All ideas, analyses, and conclusions are the author's own and have been independently verified in accordance with academic standards.

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