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GIS-Based Land Suitability Assessment for Cabbage (*Brassica oleracea* L.) Cultivation in Post-Eruption Soils of Mount Sinabung, Indonesia

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ABSTRACT: Cabbage (*Brassica oleracea* L.) is an important highland vegetable in Karo Regency, where volcanic landscapes provide agricultural potential but also create heterogeneous soil and erosion constraints. Volcanic eruptions can alter soil reaction, nutrient availability, surface stability, and land accessibility, requiring crop-specific land evaluation for sustainable post-eruption agriculture. This study assessed the actual and potential land suitability for cabbage cultivation in eruption-affected agricultural land in Naman Teran District, Karo Regency, North Sumatra, Indonesia. A Geographic Information System (GIS) was used to delineate 13 Land Mapping Units (LMUs) based on soil type, elevation, and slope. Two eruption-affected LMUs in Sigarang-garang and Sukanalu villages were evaluated using field observations, laboratory analyses of 0-30 cm soil, climate data for 2015–2024, and the FAO matching approach. Cabbage-specific land requirements were applied consistently throughout the assessment. Mean temperature (20.1°C), growing-season rainfall (583.6-593 mm), drainage, soil depth, salinity, and sodicity were generally favorable for cabbage. However, soil acidity was a major limitation, with pH values of 4.37 in LMU 1 and 5.31 in LMU 2. LMU 1 was additionally constrained by a steep 25-40% slope, whereas LMU 2 was limited by low base saturation, low organic carbon, and 15-40% surface rock fragments. Under potential suitability conditions, liming can alleviate soil acidity and organic amendments can improve soil quality, although the steep topography of LMU 1 remains a structural constraint. LMU 2 could improve to S3 if soil fertility and surface-rock limitations are effectively managed. These findings demonstrate that post-eruption land suitability cannot be inferred from volcanic soil fertility alone and that crop-specific criteria are essential for reliable land-use recommendations. The integrated GIS-FAO framework provides a practical basis for site-specific soil conservation, fertility management, and rehabilitation planning for cabbage production in volcanic highlands.

KEYWORDS: *Brassica oleracea* L., and suitability, GIS, FAO land evaluation, Mount Sinabung, volcanic soils

INTRODUCTION

Cabbage (*Brassica oleracea* L.) is an economically important cool-season vegetable whose productivity depends strongly on the interaction between climate, soil physical properties, nutrient retention, and topographic conditions. In land evaluation, the suitability of a site is therefore not determined by soil fertility alone but by the degree to which the complete set of land characteristics matches the ecological requirements of the crop. Cabbage generally performs well under cool conditions, adequate moisture, good drainage, sufficiently deep soil, and favorable soil reaction and nutrient-retention conditions (Ritung *et al*., 2011; Aliyu & Ibrahim, 2019).

Karo Regency is one of the major highland horticultural production regions of North Sumatra. Its agricultural potential is closely associated with volcanic landscapes, but the same landscapes may present substantial management challenges. Volcanic ash and other pyroclastic materials can modify soil physical and chemical properties, while steep slopes can intensify runoff and erosion. Studies of volcanic soils in Indonesia have documented wide variation in soil reaction, organic carbon, cation exchange capacity (CEC), base saturation, and phosphorus retention, depending on parent material, weathering stage, and landscape position. Mount Sinabung has been repeatedly active since 2010, producing volcanic materials that have affected agricultural land in surrounding villages. Research in Karo has shown that soils affected by the eruption can remain acidic and exhibit substantial

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spatial variability in fertility status. For example, post-eruption soils in Payung District were reported to range from low to medium fertility, with acidic reaction and variable CEC and base saturation (Marbun *et al*., 2023). More recent land evaluation work in Karo also demonstrates that post-eruption land can recover substantially over time while retaining crop-specific limitations associated with soil and climate characteristics (Sihaloho *et al*., 2026).

The FAO Framework for Land Evaluation provides a systematic basis for matching measured land characteristics with the requirements of a specified land use. Its principal advantage in post-volcanic environments is that it permits the identification of dominant limiting factors and the separation of constraints that can be improved through management from those that are difficult or impossible to modify (FAO, 1976; Ritung *et al*., 2011). GIS strengthens this approach by allowing the spatial integration of soil, terrain, climate, and land-use information and by supporting the delineation of homogeneous Land Mapping Units (LMUs). GIS-based land suitability studies have demonstrated the value of integrating crop requirements with spatial soil and climatic information for site-specific agricultural planning (Hapsari *et al*., 2014; Shao & Takeuchi, 2023).

A critical issue in crop-specific land evaluation is the use of the correct crop requirement criteria. Crop-specific consistency is essential because the suitability thresholds for temperature, soil reaction, and other land characteristics differ among crops. Cabbage-specific criteria indicate that a mean temperature of 13-24 °C and growing-season rainfall of approximately 350–800 mm are within the highly suitable range, whereas soil pH below 5.8 is a strong limitation (Ritung *et al*., 2011). Recent research on cole vegetables likewise emphasizes cool temperatures, adequate soil depth, good drainage, and careful consideration of erosion risk (Singh *et al*., 2026).

Accordingly, the present study was designed to provide a crop-specific reassessment of post-eruption agricultural land for cabbage cultivation in Naman Teran District. The study had three objectives: (1) to determine the actual land suitability of eruption-affected LMUs for cabbage;
(2) to identify the dominant physical, chemical, climatic, and topographic limiting factors; and (3) to evaluate realistic land-improvement options while explicitly distinguishing manageable constraints from permanent or difficult-to-modify constraints. The study's contribution lies not merely in producing a suitability class, but in demonstrating how crop-specific FAO matching and GIS-based LMU delineation can improve the reliability of post-eruption land-use recommendations.

MATERIALS AND METHODS

Study Area

The study was conducted from December 2025 to January 2026 in Naman Teran District, Karo Regency, North Sumatra, Indonesia. The district is approximately 20 km from Kabanjahe and 97 km from Medan and covers about 87.82 km². Elevation ranges from approximately 700 to 1,400 m above sea level. The area is an important highland horticultural production zone and includes agricultural land affected by the eruption of Mount Sinabung (Figure 1).

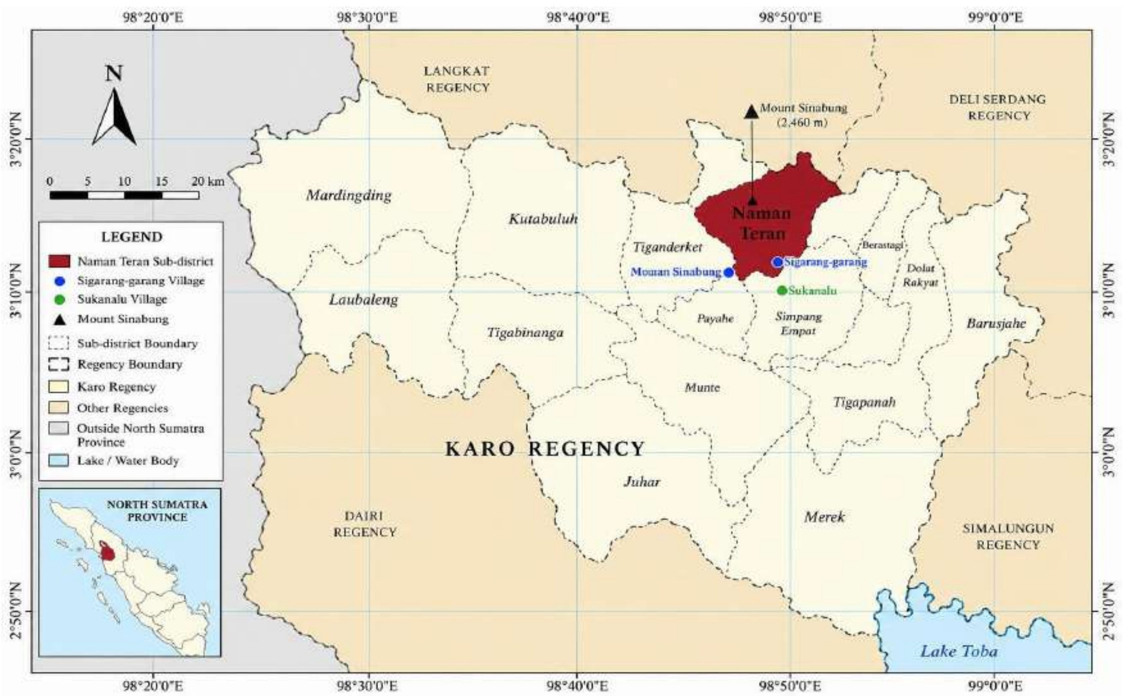

Figure 1. Location of Naman Teran District and the study area in Karo Regency.

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Land Mapping Unit Delineation

Land Mapping Units (LMUs) were delineated in a GIS environment by overlaying soil-type, elevation, and slope maps at a scale of 1:50,000. The overlay generated 13 LMUs representing distinct combinations of the major land characteristics used in the evaluation.

Among these units, LMU 1 in Sigarang-garang Village and LMU 2 in Sukanalu Village were identified as agricultural areas directly affected by the Mount Sinabung eruption and were selected for detailed field and laboratory evaluation.

Field Survey and Soil Sampling

A reconnaissance survey was conducted to verify the spatial characteristics represented by the LMUs and to identify representative sampling locations. Detailed field observations were then undertaken in the two selected LMUs. Composite surface-soil samples were collected from representative locations at 0-30 cm, corresponding to the principal surface layer relevant to cabbage establishment and nutrient management. Soil-profile observations were made to approximately 120 cm to assess morphology and effective rooting conditions.

Field observations included drainage, slope gradient, coarse fragments, effective soil depth, surface rock fragments, rock outcrops, flooding hazard, and visible erosion severity. Geographic coordinates and elevation were recorded using a GPS receiver and altimeter. These observations were integrated with laboratory and GIS data for land matching.

Laboratory Analysis

Composite soil samples were analyzed following standard laboratory procedures at the Analytical Laboratory of PT Socfin Indonesia (SOCFINDO), Medan. Soil texture, pH, CEC, base saturation, soil organic carbon, EC, exchangeable Na, and ESP were determined using standard soil analytical procedures. Detailed analytical protocols are available from the laboratory upon request. The manuscript reports the analytical values used for the final matching.

Climate Data

Secondary climate data for 2015-2024 were obtained from the Meteorology, Climatology, and Geophysical Agency (BMKG). Mean temperature, growing-season rainfall, relative humidity, and dry-month information were considered in the evaluation. Multi-year climate data were used to characterize prevailing climatic conditions rather than relying on a single season.

Cabbage-Specific Land Suitability Evaluation

Land suitability was evaluated using the FAO Framework for Land Evaluation and the matching approach (FAO, 1976). The measured characteristics of each LMU were compared with crop-specific requirements for cabbage (*Brassica oleracea* L.), primarily following Ritung *et al*. (2011). The suitability classes were S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable).

The evaluated land qualities included temperature regime, water availability, oxygen availability, rooting conditions, nutrient retention, salinity, sodicity, erosion hazard, flooding hazard, and land-preparation constraints. The final class was determined by the most restrictive characteristic under the limiting-factor approach. This approach is deliberately conservative: a single N-rated characteristic is sufficient to place the LMU in class N unless the characteristic is demonstrably manageable and the improvement scenario is explicitly defined.

Actual suitability refers to the existing condition of the land. Potential suitability refers to the condition expected after feasible management interventions. In the present study, liming was considered for soil-acidity correction, organic amendments for improving soil organic carbon and nutrient retention, surface-rock removal for land preparation, and erosion-control measures such as terracing and ground cover. However, slope itself was treated as a structural topographic property and was not assumed to disappear as a result of conservation measures. This distinction is essential when interpreting potential suitability in steep volcanic terrain.

Data Analysis

Descriptive analysis was used to summarize the measured physical, chemical, climatic, and morphological characteristics. GIS was used to integrate the LMU information and visualize the spatial context of the study area. GIS processing and spatial overlay were conducted using standard GIS procedures to delineate homogeneous land mapping units. Suitability classes were assigned through crop-specific matching, and the difference between actual and potential suitability was interpreted in relation to the manageability of the identified limiting factors.

RESULTS AND DISCUSSION

Environmental Characteristics of the Study Area

The study area represents a highland volcanic agricultural environment with elevations of approximately 700-1,400 m above sea level. The recorded mean annual temperature was 20.1°C, annual rainfall was 1,779.8 mm, and relative humidity was 87.8%. Growing-season rainfall used in the suitability table was 583.6 mm for LMU 1 and 593 mm for LMU 2. These growing-season rainfall values fall within the favorable range for cabbage under the crop-specific criteria used in this study. The mean temperature of 20.1°C is likewise within the highly suitable temperature range for cabbage and therefore should not be interpreted as a limiting factor.

The GIS overlay generated 13 LMUs. Only LMU 1 in Sigarang-garang and LMU 2 in Sukanalu were selected for detailed evaluation because these were the agricultural units identified as directly affected by the eruption. The two LMUs illustrate the spatial heterogeneity that characterizes post-eruption agricultural landscapes: apparently similar volcanic environments can exhibit different combinations of soil reaction, nutrient retention, surface rockiness, and slope.

The soil data also indicate several characteristics typical of volcanic landscapes. Volcanic materials may contribute mineral components and, during soil development, may generate favorable physical conditions; however, volcanic soils can also exhibit acidity, variable base status, and strong interactions between minerals and nutrient retention. Indonesian studies have documented substantial variation in the chemical properties of volcanic-ash-derived soils, including pH, CEC, organic carbon, and base saturation (Fiantis *et al*., 2019; Marbun *et al*., 2023). Therefore, volcanic origin should not be used as a proxy for high crop suitability without site-specific evaluation.

Cabbage-Specific Land Suitability

Application of cabbage-specific FAO matching produced a crop-specific interpretation in which climatic conditions are generally favorable and soil and topographic constraints become the principal limitations. The mean temperature of 20.1°C falls within the S1 range for cabbage and therefore does not constitute a limiting factor. Growing-season rainfall of 583.6-593 mm is also within the S1 range. The principal constraints are instead soil reaction, nutrient retention, and topographic or land-preparation conditions (Table 1).

LMU 1 had a pH of 4.37, a CEC of 10.33 cmolc kg^{-1} clay, base saturation of 14.81%, organic carbon of 1.9%, and a slope range of 25-40%. Under the cabbage criteria, the acidic pH is N, base saturation is S3, CEC is S2, and the slope range is conservatively classified as N because it extends beyond 30%. Thus, the actual suitability of LMU 1 is N, with soil acidity and steep topography as the most important constraints. The measured moderate erosion severity reinforces the need for immediate soil and water conservation.

LMU 2 had pH 5.31, CEC 11.03 cmolc kg^{-1} clay, base saturation 25.67%, organic carbon 0.47%, and surface rock fragments of 15-40%. The pH is N under the cabbage criteria, while CEC is S2, base saturation and organic carbon are S3, and surface rock fragments are S3. The slope range of 2–15% is less restrictive than that of LMU 1. Consequently, the actual suitability of LMU 2 is also N, principally because of soil acidity, with additional S3 limitations associated with nutrient retention and land preparation.

These results demonstrate why crop-specific matching is essential. If criteria from another crop are applied, the temperature of 20.1°C could be incorrectly interpreted as a limitation. Under the cabbage criteria, however, the same temperature is highly suitable. Recent studies of cabbage and other cole vegetables similarly emphasize the importance of cool temperatures, well-drained soil, adequate effective depth, soil reaction, and erosion risk (Singh *et al*., 2026; Moyin-Jesu, 2015).

Table 1. Cabbage-specific land characteristics and suitability classes for the two eruption-affected LMUs.

Land characteristic	LMU 1: Sigarang-garang	Class	LMU 2: Sukanalu	Class
Mean temperature (°C)	20.1	S1	20.1	S1
Growing-season rainfall (mm)	583.6	S1	593	S1
Relative humidity (%)	87.8	S1	87.8	S1
Drainage	Well drained	S1	Well drained	S1
Texture	Sandy clay	S1	Sandy clay	S1
Coarse fragments (%)	<15	S1	<15	S1
Soil depth (cm)	101	S1	100	S1
CEC (cmolc kg^{-1} clay)	10.33	S2	11.03	S2
Base saturation (%)	14.81	S3	25.67	S3
Soil pH (H_2O)	4.37	N	5.31	N
Organic carbon (%)	1.90	S2	0.47	S3
Salinity (dS m^{-1})	0.4714	S1	0.1823	S1
ESP (%)	1.85	S1	7.02	S1

Slope (%)	25-40	N*	2–15	S3*
Observed erosion hazard	Moderate	S2	Moderate	S2
Surface rock fragments (%)	5–15	S2	15–40	S3
Rock outcrops (%)	5–15	S2	5–15	S2
Actual suitability	N (pH, slope)		N (pH, nr, lp)	
Potential scenario	N (slope remains structural)		S3 (nr, lp)	

* The slope ranges span more than one threshold; the more restrictive class is retained for the limiting-factor evaluation. The potential scenario does not assume that slope itself is physically altered; nr = nutrient retention; lp = land preparation.

Limiting Factors in LMU 1

LMU 1 is characterized by two major constraints: strong soil acidity and steep topography. The pH of 4.37 is below the lower suitability threshold for cabbage and indicates a substantial soil-reaction limitation. Acid soils can reduce nutrient availability and may increase the activity or solubility of elements that become toxic to sensitive crops. Liming is therefore a logical corrective measure. Evidence from cabbage production systems shows that amendments capable of increasing soil pH and improving nutrient status can enhance cabbage growth and yield (Moyin-Jesu, 2015).

The second major limitation is the 25-40% slope. Under the cabbage-specific criteria, the range extends into the N class. Steep terrain is particularly important in volcanic highlands because intense rainfall can generate rapid runoff and soil loss. Erosion removes the nutrient-rich surface layer, reduces effective soil quality, and may progressively reduce the productive capacity of the site. Recent erosion-based land suitability research for cole vegetables emphasizes the strong relationship between slope, erosion hazard, and suitability in mountainous agricultural landscapes (Singh *et al*., 2026).

Terracing, contour-oriented cultivation, permanent ground cover, and residue management can substantially reduce runoff and erosion hazard. Nevertheless, these measures do not eliminate the physical slope. For this reason, the potential-suitability interpretation in this study is deliberately conservative: erosion hazard may become less restrictive, but the underlying topographic limitation remains. This is more defensible than reporting an improvement from N to S3 solely because a conservation measure is proposed without demonstrating that the slope criterion itself has changed.

Limiting Factors in LMU 2

LMU 2 has a less severe topographic constraint but stronger combined soil-fertility and land-preparation limitations. Its pH of 5.31 is below the cabbage suitability threshold and is therefore the principal reason for the actual N classification. Additional S3 limitations are associated with nutrient retention (nr) and land preparation (lp). The base saturation of 25.67% is S3, while organic carbon of 0.47% is also S3. CEC of 11.03 cmolc kg^{-1} clay is S2. These values indicate that nutrient retention and soil fertility require management even after soil acidity is corrected.

Organic amendments can increase soil organic carbon, improve aggregate stability, support microbial activity, and contribute to nutrient cycling. Experimental evidence from cabbage production has demonstrated beneficial responses to organic fertilizer and soil-amendment strategies, including improvements in soil fertility and cabbage head yield (Moyin-Jesu, 2015). In volcanic soils, management must nevertheless account for the distinctive mineralogical properties of ash-derived materials and their capacity to interact strongly with nutrients (Nurcholis et al., 2019; Fiantis *et al*., 2019). Although the slope range of LMU 2 (2-15%) is substantially less restrictive than that of LMU 1 (25-40%), it spans S1-S3 classes under the cabbage-specific criteria and was therefore conservatively rated as S3.

LMU 2 also contains 15-40% surface rock fragments. This is an S3 land-preparation limitation and may increase the difficulty and cost of tillage, bed preparation, transplanting, and crop maintenance. Removal of larger surface rocks can improve operational accessibility, but such intervention may be labor-intensive and should be evaluated economically. The combined presence of acidity, low base saturation, low organic carbon, and surface rockiness explains why LMU 2 cannot be considered highly suitable even though its climate, drainage, soil depth, salinity, and sodicity are favorable.

Potential Land Improvement and Management Implications

The distinction between actual and potential suitability is central to post-eruption land planning. Liming is the first priority in both LMUs because pH is the only N-rated soil chemical characteristic in the current dataset. The rate of lime, however, should be determined from laboratory-based lime requirement analysis rather than assumed from pH alone. Organic amendments should be used to increase soil organic carbon and improve nutrient retention, while nutrient management should be based on soil testing and crop demand.

For LMU 1, soil and water conservation should be prioritized because of the steep terrain. Contour farming, vegetative cover, mulching, and appropriately designed terraces can reduce erosion and protect the soil surface. The site should not be promoted

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as uniformly suitable for cabbage simply because soil acidity can be corrected; its structural topographic limitation remains important. A more appropriate planning approach is to identify the least-steep portions of the LMU for intensive cabbage production and use the steepest portions for conservation-oriented land cover where feasible.

For LMU 2, the management pathway is more favorable. Liming can address the pH constraint, organic amendments can improve organic carbon and nutrient retention, and surface-rock removal can reduce land-preparation constraints. Under a realistic improvement scenario, LMU 2 may reach S3 rather than S1 or S2 because some nutrient-retention characteristics, especially base saturation and CEC, remain less than optimal unless additional evidence demonstrates substantial improvement. This interpretation avoids treating potential suitability as an automatic consequence of applying amendments.

These findings are consistent with the broader understanding that volcanic landscapes can combine high agricultural potential with strong site-specific limitations. Research on volcanic soils in Indonesia shows that ash-derived soils may possess favorable physical properties but can also exhibit acid reaction, variable CEC, and strong nutrient-retention behavior (Fiantis *et al*., 2019). Recent post-Sinabung land evaluation likewise indicates that the suitability of agricultural land depends on the interaction of dynamic soil constraints with relatively persistent climatic and landscape characteristics (Sihaloho *et a*l., 2026).

Methodological Implications for GIS-Based Land Evaluation

The study demonstrates the value of combining GIS-based LMU delineation with field and laboratory measurements. GIS provides the spatial framework, but the suitability class ultimately depends on the quality and crop specificity of the land-characteristic matching. A map generated from incorrect crop thresholds can appear technically precise while producing biologically incorrect recommendations. Therefore, future studies should preserve a clear chain of evidence from crop requirement source, to measured land characteristic, to class rating, to limiting factor, and finally to management recommendation.

A second methodological implication concerns uncertainty. LMU 1 has a reported slope range of 25-40%, which crosses a suitability threshold. Rather than assigning the entire range to an intermediate class without justification, the present analysis retains the more restrictive classification. High-resolution digital elevation models, field-based slope measurements, and erosion-risk indices could refine this result. Similarly, future research should quantify post-improvement soil properties after liming and organic amendments rather than estimating potential classes solely from expected management effects.

Recent GIS and remote-sensing studies have increasingly combined multiple biophysical variables to improve crop suitability mapping. For cabbage, temperature, rainfall, soil pH, soil texture, and soil nutrient indicators have been integrated in spatial suitability models, demonstrating the importance of crop-specific environmental relationships. The present study complements these approaches by emphasizing the FAO limiting-factor framework and by explicitly distinguishing manageable soil constraints from structural topographic constraints.

Study Limitations

Three limitations should be acknowledged. First, detailed soil sampling was concentrated in two eruption-affected LMUs, so the results should not be extrapolated to all agricultural land in Naman Teran without additional sampling. Second, the potential suitability analysis represents management scenarios rather than experimentally measured post-treatment outcomes. Third, the slope information includes a range within LMU 1; higher-resolution terrain analysis would improve the precision of the erosion and topographic assessment. These limitations do not invalidate the suitability assessment, but they define the appropriate scale of inference and provide priorities for future research.

CONCLUSION

This study demonstrates that GIS-based LMU delineation integrated with the FAO land evaluation framework can identify crop-specific constraints affecting cabbage cultivation in the post-eruption agricultural landscape of Mount Sinabung. Thirteen LMUs were delineated, with LMU 1 in Sigarang-garang and LMU 2 in Sukanalu selected for detailed evaluation.

When cabbage-specific criteria are applied consistently, the climatic conditions of the two LMUs are generally favorable. The mean temperature of 20.1°C and growing-season rainfall of 583.6-593 mm are not the principal limitations for cabbage. Instead, soil reaction is the dominant chemical constraint, with pH values of 4.37 in LMU 1 and 5.31 in LMU 2. LMU 1 is additionally constrained by a steep 25-40% slope, while LMU 2 is constrained by low base saturation, low organic carbon, and substantial surface rock fragments.

Both LMUs therefore have an actual suitability class of N under the conservative limiting-factor interpretation used in this study. Liming, organic-matter management, erosion control, and surface-rock removal can reduce several manageable constraints. However, the steep topography of LMU 1 remains a structural limitation and should not be assumed to disappear following conservation treatment. LMU 2 has greater potential for improvement and may reach S3 under a realistic management scenario, subject to verification through post-treatment soil measurements. The principal contribution of this study is methodological as well as practical: reliable land suitability assessment requires strict consistency between the crop named in the study and the crop-specific criteria used for matching. For post-volcanic agricultural planning, cabbage should therefore be promoted only on sites where soil acidity, nutrient retention, erosion risk, and land-preparation constraints can be managed within economically and environmentally acceptable limits.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE (AI)

Artificial intelligence tools were used in a limited capacity to assist with language editing, consistency checking, and manuscript organization. The authors retain full responsibility for the study design, field data, laboratory data, interpretation, conclusions, and final manuscript, and all scientific content should be verified against the original research records before submission.

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