Current Science Research Bulletin
Volume 03 (11), November 2026, pp. 255-261
CrossRef DOI: 10.55677/csrb/02-V03I11Y2026
Available on: https://csrbjournal.org/

e-ISSN: 3050-7103
p-ISSN: 3050-709X

Land Suitability Assessment for Avocado Cultivation in Agricultural Areas Affected by Volcanic Materials in the Mount Sinabung Highlands, Indonesia

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ABSTRACT: This study examined land characteristics and the actual land suitability classifications reported in the source assessment for two land mapping units (LMUs) intended for avocado (Persea americana Mill.) cultivation in Naman Teran District, Karo Regency, North Sumatra, Indonesia. According to the available study records, 13 land mapping units (LMUs) were delineated using GIS. Two units, LMU 1 in Sigarang-garang and LMU 2 in Sukanalu, were purposively selected for detailed assessment based on recommendations from the sub-district government. Laboratory results reported by SOCFINDO for the two traceable composite soil samples revealed contrasting soil properties. LMU 1 had a pH of 4.37, organic carbon content of 1.90%, cation exchange capacity (CEC) of 10.33 cmolc kg−1, base saturation of 14.81%, and a loamy sand texture. LMU 2 had a pH of 5.31, organic carbon content of 0.47%, CEC of 11.04 cmolc kg−1, base saturation of 25.67%, and a sandy loam texture. The source assessment classified LMU 1 as not suitable (N) and LMU 2 as marginally suitable (S3). The findings should be interpreted as a preliminary assessment of two selected sites rather than as a definitive district-wide land suitability evaluation. These findings also identify priorities for further field verification and provide a cautious evidence base for subsequent land-use planning and site-specific management decisions concerning avocado cultivation in Naman Teran District.

KEYWORDS: avocado, land evaluation, land mapping unit, Mount Sinabung, volcanic soils

INTRODUCTION

Land evaluation is the systematic assessment of land characteristics in relation to the requirements of a specified land use. It provides a basis for land-use planning and for identifying crops suitable for local environmental conditions (Food and Agriculture Organization of the United Nations [FAO], 1976; Manalu et al., 2024; Mendas et al., 2024). A reliable evaluation considers climate, soil, terrain, and other relevant attributes collectively, as favorable conditions for one attribute may be offset by severe limitations in another (Sperandio et al., 2025).

This study focuses on two land mapping units (LMUs) within agricultural areas affected by volcanic materials from Mount Sinabung in Naman Teran District, Karo Regency, North Sumatra, Indonesia. The two LMUs were purposively selected from 13 delineated units based on recommendations from the sub-district government. The study involved an exploratory field survey, GIS-based land delineation, laboratory soil analysis, and application of the matching approach outlined in the FAO Framework for Land Evaluation (FAO, 1976; Raza et al., 2025). Soil type, elevation, and slope data were reportedly overlaid to delineate the 13 LMUs. Two units—LMU 1 in Sigarang-garang and LMU 2 in Sukanalu—were selected for detailed evaluation. Previous studies in the Sinabung-affected region also emphasize the need to characterize local soil and land conditions rather than assume uniform post-eruption properties (Lubis et al., 2021; Sihaloho et al., 2026; Winata et al., 2023).

The FAO framework distinguishes four suitability classes for a specified land use: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) (FAO, 1976). In a matching assessment, land characteristics are compared with crop

Cite the Article: *Sirait, B., Sianipar, E.M., Mendrefa, J. (2026). Land Suitability Assessment for Avocado Cultivation in Agricultural Areas Affected by Volcanic Materials in the Mount Sinabung Highlands, Indonesia. Current Science Research Bulletin, 3(11), 255-261. https://doi.org/10.55677/csrb/02-V03I11Y2026*

Publication Date: *November 12, 2026*

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requirements, and the most limiting attribute may determine the overall suitability class. Actual suitability describes land conditions at the time of evaluation, whereas potential suitability represents an estimate under a clearly defined management scenario. This distinction is particularly important when evaluating sloping land: conservation practices may reduce surface runoff and erosion, but they do not alter the natural slope gradient. Any proposed improvement in suitability must therefore be justified by evaluating each relevant attribute against explicit criteria (FAO, 1976; Nasir Ahmad et al., 2020; Singh et al., 2026).

Although avocado land suitability has been assessed in diverse agroecological environments, site-specific evaluation remains important in highlands affected by volcanic materials, where soil properties and terrain conditions may vary considerably over short distances. Previous research has evaluated avocado suitability using climatic and soil requirements, while studies in the Sinabung region have documented spatial variation in volcanic-affected soil properties (Grüter et al., 2022; Lubis et al., 2021; Winata et al., 2023). The present study compares two selected LMUs with contrasting reported slope conditions and laboratory-derived soil characteristics. Its scope is restricted to these two sites and, therefore, does not represent all agricultural land in Naman Teran District.

MATERIALS AND METHODS

Study area and climate information

The study was conducted in agricultural areas of Naman Teran District, Karo Regency, North Sumatra, Indonesia, in the highlands surrounding Mount Sinabung (Figure 1). This research was conducted from November 2025 to January 2026. The two selected study locations were Sigarang-garang (LMU 1) and Sukanalu (LMU 2), selected from 13 previously delineated land mapping units (LMUs). The original delineation was based on previous study records and could not be independently validated because the underlying GIS data and processing documentation were unavailable. The sampling procedure is illustrated in Figure 2. Since Mount Sinabung erupted again on August 31, 2026, these findings should be interpreted as reflecting conditions up to August 30, 2026



Figure 1. Location of Naman Teran District within Karo Regency, North Sumatra, Indonesia.



Figure 2. Sampling procedure

Regional climate data were obtained from a service record provided by the BMKG North Sumatra Climatology Station. The record identifies Karo Regency and Tiga Pancur Station as the relevant geographical references. Because the data originate from a regional station, they should not be interpreted as measurements taken separately at each LMU.

Land suitability was evaluated using the matching approach described in the FAO Framework for Land Evaluation (FAO, 1976). The source assessment applied four suitability classes: S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable). The avocado-specific rating thresholds were reportedly obtained from the Karo Regency Agriculture Service; however, the underlying criteria document was not available for independent verification. Consequently, the suitability classes presented here are reported as source-assessed classifications rather than independently validated classifications (FAO, 1976; Grüter et al., 2022; Lidarti et al., 2025).

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The study objectives were to: (1) describe the available soil and terrain characteristics of the two selected LMUs; and (2) report the source-assessed actual land suitability classes and identify the attributes cited as their principal limitations.

Land Suitability Evaluation for Avocado Cultivation

The available land characteristics were compared with the reported land requirements for avocado cultivation using the matching approach described in the FAO Framework for Land Evaluation (FAO, 1976). Actual suitability refers to land conditions at the time of assessment, whereas potential suitability represents an estimated class under a defined and technically feasible management scenario. Such an estimate does not establish that the proposed improvements have been implemented or experimentally validated. Any adjustment to terrain-related ratings must account for the measured natural slope and must be supported by explicit criteria (FAO, 1976; Grüter et al., 2022; Singh et al., 2026).

Climate data were obtained from Tiga Pancur Station in Karo Regency through the BMKG (Indonesian Agency for Meteorology, Climatology, and Geophysics). The dataset covered 2016–2025 and included mean annual temperature, annual rainfall, relative humidity, and dry-period duration. The complete climate dataset is not reproduced in this article; therefore, the reported values should be interpreted as regional station summaries rather than site-specific measurements.

GIS Delineation, Soil Sampling, and Laboratory Analysis

GIS layers representing soil type, elevation, and slope were reportedly integrated using ArcGIS to delineate 13 land mapping units (LMUs). Of these, the Sigarang-garang and Sukanalu areas were purposively selected for detailed assessment in accordance with the recommendations of the previous research team. Detailed methodological information—including the original GIS layers, data sources, acquisition dates, map scales, coordinate reference systems, digital elevation model (DEM) products and spatial resolutions, ArcGIS software version, and overlay procedures—is not available in the study records used for this article. Therefore, the reproducibility of the LMU delineation process cannot be independently assessed.

For each selected LMU, soil was reportedly sampled at a depth of 0–30 cm and thoroughly mixed to obtain one composite sample for laboratory analysis. The resulting laboratory data therefore characterize only the specific composite sample submitted for analysis. Accordingly, these results provide descriptive information and cannot quantify within-LMU variability.

The SOCFINDO laboratory report (SOC Ref. No. S2026-0200-01/LAB-SSPL/I/2026) provides analytical data for soil pH, cation exchange capacity (CEC), base saturation, organic carbon, salinity, exchangeable cations, and particle-size fractions. This laboratory report is the primary source for the soil analytical values presented in this article. ESP is calculated using the following formula:

$$ESP = \frac{Na\text{-exchange}}{CEC} \times 100$$

RESULTS AND DISCUSSION

3.1. Environmental and Soil Characteristics

The two selected LMUs are located in a highland agricultural landscape affected by volcanic materials (Table 1). Their reported elevations range from approximately 1,625 to 1,750 m above sea level. The regional climatic summary indicates a mean annual temperature of 20.1 °C, annual rainfall of 1,779.8 mm, and mean relative humidity of 87.8%; a dry period of 1.8 months was also reported. According to the criteria used in the source assessment, temperature, rainfall, and dry-period conditions were each classified as highly suitable (S1) for both LMUs. Avocado suitability assessments commonly consider climate together with soil and terrain constraints (Grüter et al., 2022; Lidarti et al., 2025).

LMU 1 has a reported slope of 25–40%, whereas LMU 2 has a reported slope of 2–15%. Soil pH values were 4.37 and 5.31 for LMU 1 and LMU 2, respectively. Base saturation was 14.81% in LMU 1 and 25.67% in LMU 2, while organic carbon content was 1.90% and 0.47%, respectively. The corresponding CEC values were 10.33 and 11.04 cmolc kg^{-1}, respectively. Particle-size analysis showed that LMU 1 contained 74.928% sand, 22.980% silt, and 2.0900% clay, whereas LMU 2 contained 67.410% sand, 30.550% silt, and 2.0400% clay. Soil properties in areas affected by Mount Sinabung have been reported to vary, supporting the need for site-specific characterization (Lubis et al., 2021; Jamilah & Sarifuddim, 2021; Winata et al., 2023).

Table 1 also indicates that drainage was classified as moderately suitable (S2), while soil texture was classified as marginally suitable (S3) for both LMUs in the original matching assessment. LMU 1 was described as loamy sand, whereas LMU 2 was described as sandy loam. The source assessment also reported coarse fragments of less than 15% in both LMUs.

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The presence of volcanic parent materials does not, by itself, guarantee uniform soil fertility or land suitability. Studies of soils affected by Mount Sinabung have documented variation in chemical and physical properties, including soil pH, organic carbon, exchangeable bases, and CEC. The differences observed between the two sampled composite soils therefore reinforce the importance of site-specific assessment rather than broad assumptions based solely on volcanic origin (Fiantis et al., 2019; Lubis et al., 2021; Jamilah & Sarifuddim, 2021; Winata et al., 2023).

Table 1. Reported actual and potential land suitability ratings for avocado in LMU 1 and LMU 2.

Land characteristic	LMU 1 value	Actual	Potential	LMU 2 value	Actual	Potential
Mean annual temperature (°C)	20.1	S1	S1	20.1	S1	S1
Annual rainfall (mm)	1,779.8	S1	S1	1,779.8	S1	S1
Dry period (months)	1.8	S1	S1	1.8	S1	S1
Drainage	Good to somewhat impeded	S2	S2	Good to somewhat impeded	S2	S2
Texture (source-assessed rating)	Loamy sand	S3	S3	Sandy loam	S3	S3
Coarse fragments (%)	<15	S1	S1	<15	S1	S1
Effective soil depth (cm) (information from the local community/secondary data/field information)	101	S1	S1	100	S1	S1
CEC (cmolc kg^{-1})	10.33	S1	S1	11.04	S1	S1
Base saturation (%)	14.81	S3	S1	25.67	S2	S1
Soil pH (H_2O)	4.37	S2	S1	5.31	S1	S1
Organic carbon (%)	1.90	S1	S1	0.47	S3	S1
Salinity (dS m^{-1})	0.4714	S1	S1	0.1823	S1	S1
ESP (%)	1.86	S1	S1	7.03	S1	S1
Sand (%)	74.928	—	—	67.410	—	—
Silt (%)	22.980	—	—	30.550	—	—
Clay (%)	2.0900	—	—	2.0400	—	—
Texture class (laboratory result)	Loamy sand	—	—	Sandy loam	—	—
Slope (%)	25–40	N	N	2–15	S2	S1
Erosion hazard	Moderate	S2	S2	Moderate	S2	S2
Flooding/inundation code	F0 (as reported)	S1	S1	F0 (as reported)	S1	S1
Surface rock fragments (%)	5–15	S2	S2	15–40	S3	S3
Rock outcrops (%)	5–15	S2	S2	5–15	S2	S2
Overall suitability	—	N (eh)	N (eh)	—	S3 (rc, nr, ip)	S3 (rc,nr ip)

Note: Sources of non-laboratory parameters include previous studies, information from the local community, and data from the Karo Regency Government. Abbreviations: CEC, cation exchange capacity; ESP, exchangeable sodium percentage; eh, erosion hazard; rc, rooting conditions; nr, nutrient retention; ip, land preparation. Actual suitability refers to the classification based on land conditions at the time of assessment. Potential suitability represents an estimated class under a specified management scenario. Suitability classes reported in previous assessment documents have not been independently verified in this study. A single composite soil sample per LMU characterizes only the sampled soil and does not provide a statistically representative assessment of the entire LMU.

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3.2. Spatial Differentiation Between the Selected LMUs

The GIS overlay of soil type, elevation, and slope reportedly resulted in the delineation of 13 LMUs, two of which were selected for detailed assessment. The most notable reported difference between the selected units is their slope gradient: 25–40% in LMU 1 and 2–15% in LMU 2. Slope is an important terrain attribute in agricultural land evaluation because it is related to runoff, erosion hazard, and the feasibility of land management (FAO, 1976; Mendas et al., 2024; Singh et al., 2026). However, the GIS delineation itself cannot be independently reproduced from the available records.

3.3. Actual and potential suitability of LMU 1: Sigarang-garang

LMU 1 in Sigarang-garang was classified as not suitable (N) under actual conditions in the source assessment. Its principal reported limitation was the 25–40% slope and the associated erosion hazard. Steep terrain can increase runoff and soil-loss risk and constrain access, planting operations, and the maintenance of conservation structures. Management options for consideration include contour-aligned planting, maintaining permanent or seasonal ground cover, retaining crop residues, and constructing terraces only where engineering and slope-stability assessments indicate that they are appropriate. Vegetative cover and conservation practices can reduce runoff and erosion, although their effectiveness depends on site conditions and management (Nasir Ahmad et al., 2020; Clement et al., 2024; Dahanayake et al., 2024).

Soil and water conservation can reduce erosion risk, but it does not change the natural slope gradient. The final suitability class should therefore be derived transparently from the unchanged slope value and any explicitly defined management-adjusted erosion criterion.

3.4. Actual and potential suitability of LMU 2: Sukanalu

LMU 2 in Sukanalu was classified as marginally suitable (S3) under actual conditions. Its reported slope of 2–15% is gentler than that of LMU 1, although several soil and land characteristics were identified as limitations. The measured properties of the submitted composite sample were pH 5.31, base saturation 25.67%, CEC 11.04 cmolc kg^{-1}, organic carbon 0.47%, salinity 0.1823 dS m^{-1}, and ESP 7.03%. Organic carbon was rated S3 under actual conditions. Surface rock fragments were reported to cover 15–40% of the area and were also rated S3, while rock outcrops occupied 5–15% and were rated S2. These ratings remain source-reported and require verification against the original criteria (FAO, 1976; Grüter et al., 2022; Lidarti et al., 2025).

The source assessment identifies rooting conditions, nutrient retention, and land preparation as constraints for LMU 2. Possible management options include applying suitable organic amendments, maintaining ground cover, retaining crop residues, and selectively managing rocks around planting positions where this can be done without destabilizing the soil surface. These options should be treated as recommendations for further evaluation, not as demonstrated improvements in suitability; their effectiveness depends on local soil conditions and technically appropriate implementation (FAO, 1976; Nasir Ahmad et al., 2020; Dahanayake et al., 2024).

3.5. Management implications and study limitations

The two LMUs require different management priorities. For LMU 1, the first priority is to assess slope stability and erosion risk before promoting avocado cultivation or investing in land development. Conservation measures should be selected according to site conditions and technical feasibility. For LMU 2, management may focus on improving soil organic matter, maintaining protective soil cover, and facilitating planting while avoiding practices that could increase erosion. Such interventions are consistent with general soil and water conservation principles, but their site-specific effectiveness has not been tested in this study (Nasir Ahmad et al., 2020; Clement et al., 2024; Dahanayake et al., 2024). The study did not include post-intervention measurements, field trials of avocado establishment,
or economic analyses of the proposed management practices. Therefore, potential suitability remains an estimate conditional on the feasibility and effectiveness of the proposed interventions. Under the FAO framework, potential suitability should be linked to specified land improvements and their expected effects rather than presented as an observed outcome (FAO, 1976).

Several limitations define the scope of the findings. First, only two of the 13 delineated LMUs were evaluated in detail; the results should not be generalized to all agricultural land in Naman Teran District. Second, the soil laboratory assessment was based on one composite sample per LMU from the 0–30 cm layer. This design provides descriptive characterization but does not quantify within-unit variability or support inferential statistical comparisons. Third, incomplete GIS documentation limits independent reproducibility, while the full climate dataset and the original avocado-specific rating criteria were not available for independent verification.

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CONCLUSION

The findings provide a preliminary comparison of the available soil and terrain characteristics of two selected agricultural sites in Naman Teran District. Based on the source assessment, LMU 1 (Sigarang-garang) was classified as not suitable (N), whereas LMU 2 (Sukanalu) was classified as marginally suitable (S3). However, these classifications require further verification through representative soil sampling, field-based land characterization, validation of GIS-derived attributes, and confirmation of the avocado-specific suitability criteria. Therefore, the results should be interpreted as preliminary assessments at the site level rather than definitive suitability classifications for the entire district.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE (AI)

Artificial intelligence (AI) was used in a limited capacity to assist with language editing and improving clarity. The authors retain full responsibility for the study design, data, analyses, interpretation, and final manuscript, and must verify all scientific content and references before submission.

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