

Evaluation of Soil Quality and Land Management Recommendations in Tropical Agricultural Land of Selemadeg Timur District

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ABSTRACT: Soil degradation in tropical agricultural areas threatens long-term land productivity and environmental sustainability. Soil quality assessment is therefore essential to support sustainable land management under varying biophysical conditions. This study aimed to evaluate soil quality status and identify appropriate land management directions in agricultural land of Selemadeg Timur District, Bali, Indonesia. The study was conducted across nine homogeneous land units (HLUs) representing variations in soil type, slope, and land use. Soil quality evaluation was performed using ten physical, chemical, and biological indicators as a minimum data set adapted from the Lal framework for tropical land assessment. The analyzed parameters included soil texture, bulk density, porosity, field capacity, soil pH, organic carbon, cation exchange capacity, base saturation, nutrient availability, and microbial biomass carbon. Results showed that all HLUs were classified within the “good” soil quality category, although several limiting factors differed among land units. Clay-dominated texture, low organic carbon content, nutrient imbalance, and slope-related erosion risk were identified as major constraints affecting soil function and management requirements. Variations in soil quality reflected differences in land characteristics and management practices between conventional and organic agricultural systems. Based on the identified limiting factors, recommended management strategies included organic matter improvement, nutrient management, soil conservation practices, and erosion control measures adapted to local land conditions.

KEYWORDS: Agricultural Land, Land Management, Limiting Factors, Soil Quality, Tropical Agroecosystem

I. INTRODUCTION

Land degradation remains one of the major challenges affecting agricultural sustainability in tropical regions, particularly in developing countries where agricultural land is intensively utilized under increasing environmental pressure (Riah & Tarigan, 2026). Declining soil quality can reduce land productivity, decrease nutrient availability, increase erosion susceptibility, and disrupt ecological functions that support long-term agricultural systems (Mandal *et al.*, 2023). In tropical agricultural landscapes, soil degradation is often accelerated by inappropriate land management, intensive cultivation, nutrient imbalance, low organic matter input, and topographic constraints such as sloping land (Maula, 2026).

Soil quality assessment has become an important approach for understanding the capacity of soil to maintain agricultural productivity and environmental functions. Soil quality reflects the integrated condition of physical, chemical, and biological soil properties that influence plant growth, water regulation, nutrient cycling, and ecosystem stability (Xing *et al.*, 2025). Evaluation of soil quality is therefore essential not only for identifying land limitations, but also for supporting sustainable land management and conservation planning in agricultural areas.

Various approaches have been developed to evaluate soil quality using selected indicators that represent soil functions under specific environmental conditions. Among these approaches, the framework introduced by Lal, (1994) has been widely applied in tropical land assessment due to its operational simplicity and its ability to identify dominant limiting factors affecting soil performance (Febriana *et al.*, 2024; Triadiawarman *et al.*, 2022; Setiawan *et al.*, 2026). The approach integrates several minimum data set indicators representing physical, chemical, and biological soil properties to classify soil quality status and support land management interpretation. However, soil quality assessment in tropical agricultural regions remains highly contextual because soil response is influenced by variations in soil type, slope, land use, and management practices (Abshiba *et al.*, 2025).

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Agricultural landscapes in tropical areas commonly exhibit heterogeneous biophysical conditions that may generate different soil constraints and management requirements between land units. Therefore, interpretation of soil quality should not only focus on classification results, but also on understanding limiting factors and their implications for land management under local environmental conditions.

Selemadeg Timur District, Bali, represents a tropical agricultural area characterized by diverse land use systems, topographic variation, and different soil types. These conditions provide an important basis for evaluating soil quality and identifying management directions suitable for maintaining soil function and agricultural sustainability. Information regarding soil quality status and limiting factors in this area remains limited, particularly in relation to practical land management recommendations adapted to local land characteristics. This study aimed to evaluate soil quality status and identify land management directions in agricultural land of Selemadeg Timur District using selected physical, chemical, and biological soil indicators based on the Lal framework for tropical land assessment.

II. RESEARCH METHOD

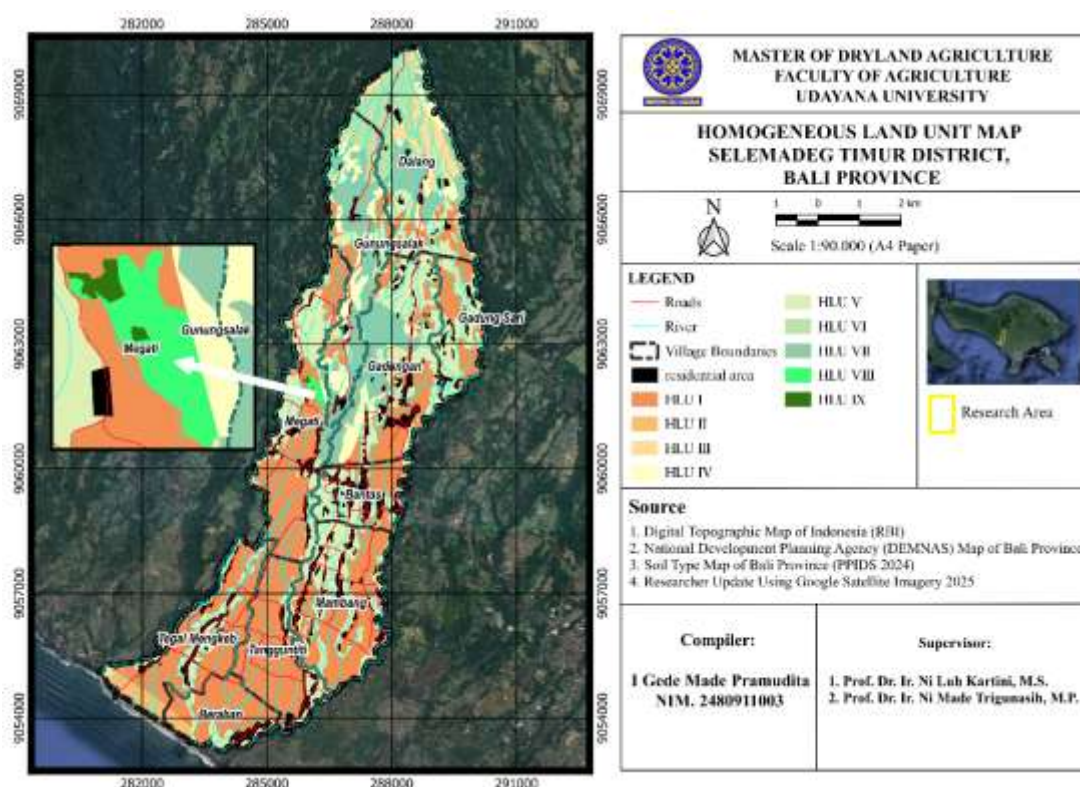
A. Study Area and Research Design

This study adopted a quantitative approach integrating field surveys and laboratory analyses to assess agricultural soil quality. The research was conducted in East Selemadeg District, Tabanan Regency, Bali, Indonesia, a tropical agroecosystem characterized by heterogeneous biophysical conditions, including variations in soil type, slope, and land use. This study aimed to evaluate soil quality status for each Homogenous Land Unit (HLU) and identify appropriate land management directions for each HLUs in agricultural land of Selemadeg Timur District, Bali, Indonesia.

B. Homogeneous Land Unit Delineation and Soil Sampling

HLUs were established through an overlay analysis of soil type, slope, and land use maps. In this study, the HLU creation process was conducted using QGIS 3.28.5, spanning from delineation and overlay to map layouting. This procedure generated nine HLUs representing distinct combinations of biophysical characteristics. These units served as the basis for soil quality assessment. The HLU map of this study is presented in Figure 1. Soil sampling was carried out in each HLU using purposive sampling. Composite soil samples were collected from several observation points within each unit to capture representative field conditions. For areas identified as paddy fields, sampling was conducted at a depth of 0–30 cm. Meanwhile, sampling for mixed gardens covered a depth of 0–60 cm, adjusting to the root depth of the crops in each land type.

C. Soil Quality Indicators and Laboratory Analysis



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Ten soil quality indicators were selected as the Minimum Data Set (MDS), including physical, chemical, and biological soil properties. The selected indicators were intended to reflect actual field conditions, remain sensitive to environmental disturbances, and represent dominant soil degradation processes. In addition, all indicators were measurable, applicable under limited laboratory facilities, and relevant across spatial and temporal scales. The MDS was designed to capture integrated soil processes while maintaining ecological relevance to local environmental conditions.

The physical indicators consisted of soil texture (pipette method), bulk density and porosity (core ring method), and field capacity moisture content (gravimetric method). Chemical indicators included soil organic carbon (Walkley–Black method), soil pH (H₂O 1:2.5 potentiometric method), total nitrogen (Kjeldahl method), available phosphorus and potassium (Bray I extraction), cation exchange capacity (CEC), and base saturation (1 N NH₄OAc extraction at pH 7). The biological indicator was microbial biomass carbon, determined using the soil respiration method.

D. Soil Quality Assessment Based on Lal (1994)

Soil quality was evaluated using the limiting factor approach proposed by Lal (1994). Each MDS indicator was assigned a score ranging from 1 to 5, where lower scores indicated more favorable soil conditions (Pramudita et al., 2024; Setiawan et al., 2026). The Soil Quality Index (SQI) was calculated as:

$$SQI = PP + CP + BP$$

where PP represents the cumulative score of physical indicators, CP represents the cumulative score of chemical indicators, and BP represents the cumulative score of biological indicators.

The resulting SQI values were classified into five categories following Lal (1994): very good (<20), good (20–25), moderate (25–30), poor (30–40), and very poor (>40). The threshold values used for scoring individual indicators are presented in Table 1.

Table 1. Limiting Factors and Relative Weighting of Soil Quality Indicators

No	Indicators	Limiting Factor and relative weight				
		Without	Light	Medium	Heavy	Extreme
		1	2	3	4	5
1	Bulk Density (g cm ⁻³)	<1,2	1,3-1,4	1,4-1,5	1,5-1,6	>1,6
2	Soil Texture	L	SiL, Si, SiCL	CL, SL	SiC, LS	S, C
3	Porosity (%)	>20	18-20	15-18	10-15	<10
4	Water field capacity (%)	>30	20-30	8-20	2-8	<2
5	SOC (%)	5-10	3-5	1-3	0,5-1	<0,5
6	pH	6,0-7,0	5,8-6,0	5,4-5,8	5,0-5,4	<5,0
7	CEC (me/100g)	>40	25-40	17-24	5-16	<5
8	BS (%)	>70	51-70	36-50	20-35	<20
9	Nutrient (N,P dan K)					
	N-total (%)	>0,75	0,51- 0,75	0,21-0,50	0,10-0,20	<0,10
	Available-P (ppm)	>35	26-35	16-25	10-15	<10
	Available-K (ppm)	>1,0	0,6-1,0	0,3-0,5	0,1-0,2	<0,1
10	C-biomass (mg C-CO ₂ kg ⁻¹)	>25	20-25	10-20	5-10	<5

Note: L=Loam; Si = Silt; S= Sand; C=Clay. Source : Lal (1994).

III. RESULTS

A. Characteristics of Study Area

The first outcome of this study is the delineation and characterization of homogeneous land units (HLUs) based on the overlay of soil type, slope gradient, land use, and agricultural management systems. Nine HLUs were identified, reflecting the biophysical heterogeneity of the study area. Such variability may contribute to differences in soil formation processes, land management responses, and the observed variation in individual soil quality indicators. The characteristics of the identified HLUs are presented in Table 2.

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Table 2. Biophysical Characteristics of Each HLU

HLU	Land Location (Village)	Land area (ha)	Soil Type	Slope (%)	Land Use
I	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	2.194,55	Yellowish brown latosol	0 – 8	Conventional rice fields
II	Tegal Mengkeb, Beraban	97,59	Grayish brown regosol	0 – 8	Conventional rice fields
III	Gunung Salak, Dalang, Beraban	161,68	Yellowish brown latosol	8 – 15	Conventional rice fields
IV	Dalang, Gadungan, Gunung Salak, Megati	319,05	Yellowish brown latosol	15 – 25	Conventional rice fields
V	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	1681,47	Yellowish brown latosol	0 – 8	Conventional Mixed dryland farming
VI	Gunung Salak, Dalang	302,93	Yellowish brown latosol	8 – 15	Conventional Mixed dryland farming
VII	Gadungan, Gunung Salak, Megati, Dalang	700,54	Yellowish brown latosol	15 – 25	Conventional Mixed dryland farming
VIII	Megati	17,94	Yellowish brown latosol	0 – 8	Organic Mixed dryland farming
IX	Megati	2,25	Yellowish brown latosol	15 – 25	Organic rice field

B. Physical Soil Properties

Physical soil properties were evaluated to characterize fundamental soil conditions that influence water retention, soil aeration, and the overall capacity of soil to support plant growth. Variations in physical properties among homogeneous land units (HLUs) reflect the combined effects of parent material, slope gradient, and land-use history, which collectively shape soil development and functionality. In this study, physical soil assessment included soil texture, bulk density, total porosity, and field capacity. The analytical results for these parameters are presented in Table 3.

C. Chemical Soil Properties

Chemical soil properties were evaluated to assess soil fertility status, particularly in relation to nutrient availability and the chemical environment that governs soil processes. Soil chemical indicators were selected following the soil quality assessment framework proposed by Lal (1994), including soil pH, organic carbon content, cation exchange capacity (CEC), base saturation (BS), and nutrient availability represented by total nitrogen (N), available phosphorus (P), and available potassium (K). The results revealed noticeable variations among homogeneous land units (HLUs), reflecting differences in land characteristics and management practices across the study area. The analytical results of the chemical soil properties are presented in Table 4.

Table 3. Analysis Results of Soil Physical Parameters

HLU	Bulk Density (g cm ⁻³)	Soil Texture	Porosity (%)	Field Capacity (%)	Total score
I	1,11 ₍₁₎	Clay ₍₅₎	58.11 ₍₁₎	33.10 ₍₁₎	8
II	1,48 ₍₃₎	Silty Loam ₍₂₎	44.15 ₍₁₎	30,03 ₍₁₎	7
III	1,13 ₍₁₎	Clay ₍₅₎	57.36 ₍₁₎	35.52 ₍₁₎	8
IV	1,20 ₍₁₎	Clay ₍₅₎	55.09 ₍₁₎	37.49 ₍₁₎	8
V	1,06 ₍₁₎	Clay ₍₅₎	60.00 ₍₁₎	40.66 ₍₁₎	8
VI	1,21 ₍₁₎	Clay ₍₅₎	54.34 ₍₁₎	36.50 ₍₁₎	8
VII	1,04 ₍₁₎	Clay ₍₅₎	61.13 ₍₁₎	34.46 ₍₁₎	8
VIII	1,21 ₍₁₎	Clay ₍₅₎	54.34 ₍₁₎	41.64 ₍₁₎	8
IX	1,43 ₍₃₎	Clay ₍₅₎	46.04 ₍₁₎	34.16 ₍₁₎	10

Note: Relative weights & Limiting factors: (1) None, (2) Slight, (3) Moderate, (4) Severe, (5) Extreme

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Table 4. Analysis Results of Soil Chemical Parameters

HLU	C-organik (%)	pH	KTK (me 100g ⁻¹)	KB (%)	Nutrition			Mean score of N, P, and K parameters	Total score
					N-total (%)	P-tersedia (ppm)	K-tersedia (ppm)		
I	1,77 ₍₃₎	7,08 ₍₁₎	29,99 ₍₂₎	33,33 ₍₁₎	0,18 ₍₄₎	24,09 ₍₃₎	202,77 ₍₁₎	2,66	
II	1,74 ₍₃₎	6,83 ₍₁₎	32,40 ₍₂₎	93,79 ₍₁₎	0,17 ₍₄₎	25,6 ₍₃₎	162,66 ₍₁₎	2,66	
III	2,59 ₍₃₎	5,85 ₍₂₎	29,08 ₍₂₎	84,44 ₍₁₎	0,22 ₍₃₎	7,22 ₍₅₎	154,36 ₍₁₎	3	
IV	3,45 ₍₂₎	6,12 ₍₁₎	20,61 ₍₃₎	90,32 ₍₁₎	0,25 ₍₃₎	2,26 ₍₅₎	157,45 ₍₁₎	3	
V	2,18 ₍₃₎	6,50 ₍₁₎	23,02 ₍₃₎	96,78 ₍₁₎	0,21 ₍₃₎	2,29 ₍₅₎	160,85 ₍₁₎	3	
VI	3,04 ₍₂₎	6,47 ₍₁₎	25,40 ₍₂₎	91,23 ₍₁₎	0,22 ₍₃₎	2,27 ₍₅₎	162,42 ₍₁₎	3	
VII	3,44 ₍₂₎	6,53 ₍₁₎	26,07 ₍₂₎	13,56 ₍₁₎	0,23 ₍₃₎	6,37 ₍₅₎	16,95 ₍₁₎	3	
VIII	3,48 ₍₂₎	6,57 ₍₁₎	27,93 ₍₂₎	83,20 ₍₁₎	0,22 ₍₃₎	2,28 ₍₅₎	140,66 ₍₁₎	3	
IX	3,05 ₍₂₎	6,79 ₍₁₎	26,28 ₍₂₎	27,05 ₍₁₎	0,31 ₍₃₎	24,51 ₍₃₎	208,91 ₍₁₎	2,3	

Note: Relative weights & Limiting factors: (1) None, (2) Slight, (3) Moderate, (4) Severe, (5) Extreme

D. Biological Soil Properties

Biological soil properties are increasingly recognized as essential components of soil quality because they directly reflect the biological processes that sustain ecosystem functioning. Microbial biomass carbon (MBC), one of the most widely used biological indicators in soil quality assessment, represents the living fraction of soil organic matter and serves as an important indicator of microbial activity, nutrient turnover, and soil resilience. Changes in MBC often provide an early signal of shifts in soil condition resulting from land use and management practices. Therefore, MBC was selected as the biological indicator in this study to complement the evaluation of physical and chemical soil properties. The results of the MBC analysis for each homogeneous land unit (HLU) are presented in Table 5.

Table 5. Analysis Results of Soil Biological Parameters

HLU	HLU I	HLU II	HLU III	HLU IV	HLU V	HLU VI	HLU VII	HLU VIII	HLU IX
MBC (mg C-CO ₂ kg ⁻¹)	1,8 ₍₅₎	0,94 ₍₅₎	3,52 ₍₅₎	11,52 ₍₃₎	3,23 ₍₅₎	0,94 ₍₅₎	2,37 ₍₅₎	2,09 ₍₅₎	3,23 ₍₅₎

Note: Relative weights & Limiting factors: (1) None, (2) Slight, (3) Moderate, (4) Severe, (5) Extreme

E. Soil Quality Index

The Soil Quality Index (SQI) was determined using a Minimum Data Set (MDS) of ten physical, chemical, and biological parameters based on Lal (1994). Data were integrated into a unified evaluation matrix, where each parameter was compared against standard criteria (Table 1) and assigned a limitation score from 1 (optimal/minor limitation) to 5 (severe constraint). Following Lal (1994), an unweighted cumulative score was calculated by summing all ten parameter scores for each Homogeneous Land Unit (HLU), serving as the definitive SQI value. These values were then categorized into soil quality classes based on Lal's classification threshold: very good (<20), good (20–25), moderate (25–30), poor (30–40), and very poor (>40). The evaluation stages are summarized in Table 6.

Table 6. Soil Quality Index in Selemadeg Timur District

HLU	CP	PP	BP	SQI
I	9,6	8	5	22,66
II	9,6	7	5	21,66
III	11	8	5	24
IV	10	8	3	21
V	11	8	5	24
VI	9	8	5	22
VII	9	8	5	22
VIII	9	8	5	22
IX	8,3	10	5	23,33

Note: CP= Chemical Parameters, PP= Physical Parameters, BP= Biological Parameters

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Table 7. Soil Quality Status and Distribution in Selemadeg Timur District

HLU	Land Location (Village)	Land Area (ha)	SQI	Soil Quality Status
I	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	2.194,55	22,6	Good (2)
II	Tegal Mengkeb, Beraban	97,59	21,6	Good (2)
III	Gunung Salak, Dalang, Beraban	161,68	24	Good (2)
IV	Dalang, Gadungan, Gunung Salak, Megati	319,05	21	Good (2)
V	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	1681,47	24	Good (2)
VI	Gunung Salak, Dalang	302,93	22	Good (2)
VII	Gadungan, Gunung Salak, Megati, Dalang	700,54	22	Good (2)
VIII	Megati	17,94	22	Good (2)
IX	Megati	2,25	23,3	Good (2)

IV. DISCUSSION

A. Soil Quality Status

Soil quality across all HLUs in the East Selemadeg Subdistrict was uniformly classified as 'good'. However, variations emerged at the index level, with SQI values fluctuating between 21 and 24. This divergence reflects subtle differences in the number and severity of limiting factors within each HLU. Lower SQI values denote near-optimal soil conditions with minimal constraints, whereas higher values indicate an accumulation of more pronounced physical, chemical, or biological limitations. These findings highlight that while all locations fall within the same 'good' class, soil quality is not absolutely homogeneous but exhibits a nuanced, quantifiable spectrum distinguishable at the index level.

The observed variation in soil quality index (SQI) values among HLUs can be attributed to differences in physical, chemical, and biological soil properties that collectively influence soil functioning. Although all land units were classified within the same soil quality category, variations in texture, nutrient status, organic carbon content, microbial activity, and topographic conditions contributed to differences in the number and intensity of limiting factors. These findings highlight that soil quality is governed by the interaction of multiple soil attributes rather than by a single dominant property, emphasizing the importance of integrated assessment approaches for evaluating soil function and agricultural sustainability.

B. Physical, Chemical, and Biological Factors Influencing Soil Quality

From a physical perspective, soil texture emerged as one of the dominant factors influencing soil quality. Most HLUs were characterized by clay-rich soils, which generally exhibit greater water retention capacity and nutrient-holding potential due to their high specific surface area. However, the predominance of micropores in clay soils may simultaneously restrict permeability and soil aeration, potentially limiting root development under poorly drained conditions. This finding highlights the dual role of clay as both a beneficial and limiting factor in agricultural soils, depending on the balance between water retention and aeration. The influence of soil texture was further reflected in the relationship between bulk density, porosity, and field capacity (Hun *et al.*, 2026). Bulk density and total porosity exhibited a clear inverse relationship, indicating that increasing soil compaction reduces pore space available for water movement, root penetration, and gaseous exchange. Similarly, field capacity was closely associated with soil texture, where finer-textured soils generally retained more water than coarser-textured soils. These interactions emphasize the importance of soil physical structure in maintaining favorable conditions for plant growth and soil functioning. An interesting observation was identified in HLU II, where cultivated Regosol exhibited a silty loam texture rather than the coarse texture commonly associated with young Regosols. This condition suggests that long-term agricultural management, together with depositional and pedogenic processes, may gradually modify the physical characteristics traditionally associated with specific soil types. Similar trends have been reported in intensively managed agricultural systems where the accumulation of fine particles and organic materials contributes to the development of finer soil textures over time (Machado *et al.*, 2023). Topographic variation also played an important role in shaping soil quality. The interaction between clay-rich soils and steeper slopes may increase susceptibility to surface runoff and soil erosion, particularly under conditions of inadequate soil conservation. Because topsoil contains a substantial proportion of organic matter and plant nutrients, erosion-induced soil loss may gradually reduce soil

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productivity and ecological functioning. This finding highlights the importance of conservation-oriented land management practices in sloping agricultural landscapes.

Chemical soil properties further explained the variation in soil quality across the study area. Soil pH is widely recognized as a key regulator of nutrient availability because it influences nutrient uptake efficiency and the solubility of potentially toxic elements (Zhou, 2024). Most HLUs exhibited soil pH values within the range considered favorable for nutrient availability, indicating generally suitable chemical conditions for agricultural production. In addition, soil pH, cation exchange capacity (CEC), and base saturation (BS) are closely interconnected indicators that collectively reflect soil fertility status and nutrient retention capacity (Albuquerque *et al.*, 2024). The generally favorable values observed for these parameters suggest that the soils possess adequate capacity to retain and supply essential nutrients for plant growth. Among the evaluated chemical indicators, organic carbon emerged as a particularly important determinant of soil quality. Soil organic carbon contributes to nutrient retention, aggregate stability, and microbial activity, making it a central component of soil functioning and long-term soil fertility (Li *et al.*, 2024). Differences in organic carbon content among HLUs likely reflected variations in land use and management practices. Mixed-cropping systems generally maintained higher organic carbon levels than paddy fields, which may be attributed to continuous organic matter inputs from plant residues and lower levels of soil disturbance. Previous studies have shown that reduced soil disturbance under conservation-oriented management can enhance soil structure stability, improve carbon sequestration, and promote long-term soil sustainability (Das *et al.*, 2022; Veloso *et al.*, 2025).

Biological soil properties complemented the assessment of physical and chemical conditions. Microbial biomass carbon (MBC), which represents the living fraction of soil organic matter, is widely used as an indicator of biological activity and soil health. Because microbial communities respond rapidly to environmental changes and management interventions, MBC can provide valuable information regarding the biological functioning of agricultural soils (Cai *et al.*, 2025). The observed variation in MBC among HLUs may be linked to differences in organic matter availability and land management practices. Furthermore, the close relationship between soil organic carbon and microbial biomass highlights the importance of maintaining adequate organic matter inputs to sustain nutrient cycling, microbial activity, and overall soil quality. Collectively, these findings demonstrate that soil quality is governed by the interaction of physical, chemical, and biological processes, emphasizing the need for integrated management approaches to maintain sustainable agricultural production.

C. Limiting Factors of Soil Quality

Limiting factors in this study were identified based on indicators classified as moderate (Class 3), severe (Class 4), or extreme (Class 5). These levels represent constraints with the potential to significantly impair soil functions and were therefore prioritized for management intervention. The classification results for each indicator are summarized in Tables 3–5. The analysis revealed that the dominant limiting factors varied among HLUs but were generally associated with soil texture, nutrient availability, organic carbon content, and microbial biomass carbon. Their presence contributed to variations in SQI values and may influence the long-term sustainability of agricultural production if left unmanaged.

The occurrence of multiple limiting factors within a single land unit highlights the importance of integrated soil management. Soil quality is influenced by the interaction of physical, chemical, and biological processes; therefore, management strategies should address underlying constraints collectively rather than focusing on individual indicators in isolation.

D. Soil Management Recommendations

Among the proposed interventions, increasing organic matter inputs emerged as the most broadly applicable strategy. Organic amendments such as compost, manure, crop residues, and other locally available biomass sources can simultaneously improve multiple soil functions. In addition to increasing soil organic carbon, organic matter promotes microbial activity, enhances aggregate stability, improves porosity and water retention, and contributes to nutrient cycling. Because many physical, chemical, and biological soil properties are interconnected, organic matter management represents a practical approach for improving overall soil quality rather than addressing individual limitations separately (Liu *et al.*, 2022).

Soil texture was identified as one of the dominant physical constraints in several HLUs. Although soil texture itself is largely determined by inherent soil properties and cannot be readily altered through management, its effects can be mitigated by improving soil structure (Basset *et al.*, 2023; Giuliani *et al.*, 2024). Organic matter plays an important role in aggregate formation, thereby improving aeration, water movement, root penetration, and resistance to compaction. These improvements are particularly important in clay-dominated soils, where excessive water retention and limited aeration may restrict plant growth.

Nutrient management should be integrated with soil quality improvement efforts. Balanced fertilization remains essential for maintaining adequate nutrient availability; however, the effectiveness of nutrient inputs depends strongly on soil conditions. Organic amendments not only provide supplementary nutrients but also improve nutrient retention and reduce losses through

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leaching and other pathways. In tropical soils, organic matter may further enhance phosphorus availability by reducing phosphorus fixation and increasing nutrient accessibility for plants (Islam *et al.*, 2026).

The results also emphasize the importance of adaptive management in mixed-cropping systems, where nutrient requirements vary among plant species and growth stages. Rather than relying on uniform fertilizer applications, nutrient management should consider crop characteristics, soil conditions, and local management objectives. Such an approach is more consistent with sustainable land management principles and can improve nutrient-use efficiency while minimizing environmental impacts.

For land units characterized by lower cation exchange capacity, management efforts should focus on increasing soil organic matter while maintaining favorable soil pH conditions. Because both humus content and soil reaction influence the development of exchange sites, improvements in nutrient retention capacity are most effective when organic matter enhancement is accompanied by appropriate pH management. Collectively, these findings indicate that integrated management strategies combining organic matter inputs, balanced nutrient management, soil conservation, and adaptive land-use practices offer the greatest potential for sustaining soil quality in tropical agricultural landscapes. Detailed soil management recommendations for each HLU, including the corresponding village areas and the specific limiting factors addressed by each management strategy, are presented in Table 8.

Table 8. Soil Management Recommendations Based on Identified Limiting Factors

HLU	Village Areas	Major Limiting Factors	Recommended Management
I	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	Organic carbon (3), microbial biomass carbon (5), soil texture (5)	Application of organic amendments (compost, manure, crop residues) to improve soil organic matter and biological activity; soil structure improvement through organic matter management.
II	Tegal Mengkeb, Beraban	Organic carbon (3), microbial biomass carbon (5), bulk density (3)	Organic matter application to improve soil organic carbon and biological activity; adaptive tillage practices to reduce soil compaction and improve soil structure.
III	Gunung Salak, Dalang, Beraban	Organic carbon (3), microbial biomass carbon (5), CEC (3), nutrients: N (3), P (5), soil texture (5)	Organic matter application; balanced fertilization to improve N and P availability; soil structure improvement through organic amendments and appropriate tillage practices.
IV	Dalang, Gadungan, Gunung Salak, Megati	Nutrients: N (3), P (5), CEC (3), microbial biomass carbon (3), soil texture (5)	Balanced fertilization combined with organic amendments to improve nutrient availability, microbial activity, and soil physical condition.
V	Bantas, Mambang, Beraban, Tangguntiti, Tegal Mengkeb, Megati, Gunung Salak, Gadungan, Gadung Sari	Organic carbon (3), microbial biomass carbon (5), CEC (4), soil texture (3), nutrients: N (3), P (5)	Organic matter application to improve soil fertility, CEC, and biological activity; balanced fertilization and adaptive tillage practices.
VI	Gunung Salak, Dalang	Nutrients: N (3), P (5), microbial biomass carbon (5), soil texture (4)	Balanced fertilization; organic matter application to enhance biological activity and improve soil physical properties.
VII	Gadungan, Gunung Salak, Megati, Dalang	Nutrients: N (3), P (5), microbial biomass carbon (5), soil texture (5)	Balanced fertilization combined with organic matter inputs and soil structure improvement measures.
VIII	Megati	Nutrients: N (3), P (5), microbial biomass carbon (5), soil texture (5)	Balanced fertilization and organic matter application to improve nutrient availability, biological activity, and soil structure.
IX	Megati	Bulk density (3), microbial biomass carbon (5), soil texture (5)	Organic matter application and adaptive tillage practices to reduce compaction and improve soil physical condition.

V. CONCLUSIONS

The agricultural soils of East Selemadeg Subdistrict were generally characterized by good soil quality status, although variations in soil quality index values indicated the presence of differing physical, chemical, and biological constraints among homogeneous

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land units. Soil texture, organic carbon content, nutrient status, microbial biomass carbon, and topographic conditions were identified as the principal factors influencing soil quality and contributing to the observed variability across the study area.

The results emphasize that soil quality is governed by the interaction of multiple soil functions and therefore requires integrated management strategies. Practices that enhance organic matter accumulation, improve nutrient-use efficiency, maintain biological activity, and reduce erosion risk are expected to provide the greatest benefits for sustaining soil functions over the long term. These findings underscore the value of soil quality assessment as a practical tool for guiding land management decisions and promoting the sustainable management of tropical agricultural landscapes.

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