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Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

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ABSTRACT: This study is a descriptive field–laboratory research aimed at evaluating the soil fertility status in the Subak Selumbung area, Manggis District, Karangasem Regency, Bali Province, an agricultural region that highly depends on the sustainability of soil functions. The objectives of this study were to assess soil fertility based on key chemical properties, identify fertility-limiting factors, and formulate recommendations for sustainable land management. Soil samples were collected through field surveys and analyzed in the Soil Chemistry Laboratory to determine several chemical parameters, including Cation Exchange Capacity (CEC), Base Saturation (BS), organic carbon (C-organic), total phosphorus (P-total), and total potassium (K-total). The results showed that CEC ranged from 21.87 to 28.07 me/100 g (moderate to high), BS was very high (81.89–99.01%), organic carbon content was low to moderate, while total P and K levels were high to very high. Based on these indicators, soil fertility in Selumbung was classified into two categories: high (SLH II, III, IV, and VI) and moderate (SLH I and V). The main limiting factor was the low organic matter content associated with reduced biological activity. To address this constraint, the application of organic fertilizers (compost, manure, and green manure), balanced NPK fertilization, and the implementation of soil and water conservation practices such as terracing, cover cropping, and surface water regulation are recommended. Spatial mapping using a Geographic Information System (GIS) also revealed variations in fertility levels among land units, providing a scientific basis for sustainable agricultural land management in the Karangasem region.

KEYWORDS: Subak Selumbung, soil fertility, soil chemical properties, GIS, sustainable land management.

INTRODUCTION

Selumbung Village is an agricultural area located in Manggis District, Karangasem Regency, Bali Province. The village consists of Banjar Dinas Kaleran, Kanginan, Tengah, Kelodan, Anyar, and Bukit Catu, with a total population of 3,787 people comprising 1,910 males and 1,877 females. The total land area of 412.16 hectares is utilized for various purposes, including 20.12 hectares of rice fields, 40.20 hectares of dryland, 281.26 hectares of plantations, and 70.58 hectares of settlements. Agricultural commodities cultivated in this region vary according to land type. Rice and secondary crops are grown in wetland farming systems through monoculture and mixed cropping. Farmers generally apply a planting pattern of two cycles of rice and one cycle of secondary crops each year, supported by intensive application of NPK fertilizers. In recent years, however, several subak have faced water scarcity, which has forced farmers to plant rice only during the rainy season and secondary crops afterward. On dryland areas, perennial crops such as banana, coconut, and cocoa are cultivated under mixed cropping systems (Sumedana 2024).

Increasing population and technological development have intensified land use demands, making proper land management essential. Soil characteristics vary among regions and determine the capacity of land to support agricultural productivity (Muliarta & Purba, 2020). Poor land management can reduce land productivity, resulting in crop yields that fall below optimal levels and reflecting a decline in land function. Soil quality and fertility decrease when the land is not managed wisely (Sumarniasih et al. 2021). In contrast, appropriate tillage practices play an important role in determining plant growth and yield (Trigunasih & Dibia, 2019).

Soil fertility is defined as the ability of soil to supply essential nutrients in sufficient quantities and balanced forms to support optimal plant growth and production. This ability differs among soils and depends on inherent properties and management practices (Ceunfin et al. 2022). Variations in fertility levels are influenced by the strategies applied in managing the land, which directly affect crop productivity (Susila et al. 2024). Therefore, an evaluation of soil fertility status is necessary to identify nutrient limitations and determine suitable management interventions.

Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

Soil fertility assessment can be conducted through soil testing, which provides accurate and efficient results. The evaluation considers chemical parameters such as pH, Cation Exchange Capacity, Base Saturation, organic carbon, total phosphorus, and total potassium, following established guidelines for soil fertility assessment (PPT 1995, Prabowo and Subantoro 2018). In addition to laboratory analysis, advancements in technology, particularly Geographic Information Systems, support spatial evaluation and management. Geographic Information Systems allow the collection, processing, analysis, storage, and presentation of spatial data. This technology is widely used in agriculture for land suitability analysis, land degradation monitoring, land use assessment, irrigation planning, and agricultural development planning (Setianingrum et al. 2014).

Considering these conditions, evaluation of soil fertility status in Selumbung Village is highly important because updated information regarding current soil fertility conditions is not yet available. The findings of this study will provide baseline data and serve as a reference for guiding soil fertility management to support productive, profitable, and sustainable agricultural practices.

RESEARCH METHOD

Research Design

This study employed a survey method combined with laboratory soil analysis to determine soil fertility status based on the Technical Guidelines for Soil Fertility Evaluation published in 1995. The survey method was used to identify homogeneous land units by examining similarities in land use, slope conditions, and soil type. Soil sampling was conducted at each homogeneous land unit, and the collected samples were subsequently analyzed in the laboratory to assess chemical soil properties.

The evaluated soil fertility parameters included cation exchange capacity measured using ammonium acetate one normal at pH seven, base saturation measured using ammonium acetate one normal at pH seven, organic carbon measured using the Walkley and Black method, total potassium measured using hydrochloric acid twenty five percent, total phosphorus measured using hydrochloric acid twenty five percent, and pH measured in water.

The soil fertility status was determined by comparing the laboratory results with the criteria stated in the Technical Guidelines for Soil Fertility Evaluation published in 1995.

Research Location and Time

The research was conducted from June two thousand twenty five to August two thousand twenty five in Selumbung Village, Manggis District. Geographically, the site is located at coordinates eight point four eight three one four five zero south latitude and one hundred fifteen point five two eight five six eight zero east longitude.

The analysis of chemical soil properties was carried out at the Soil Laboratory of the Master Program in Dryland Agriculture, Faculty of Agriculture, Udayana University.

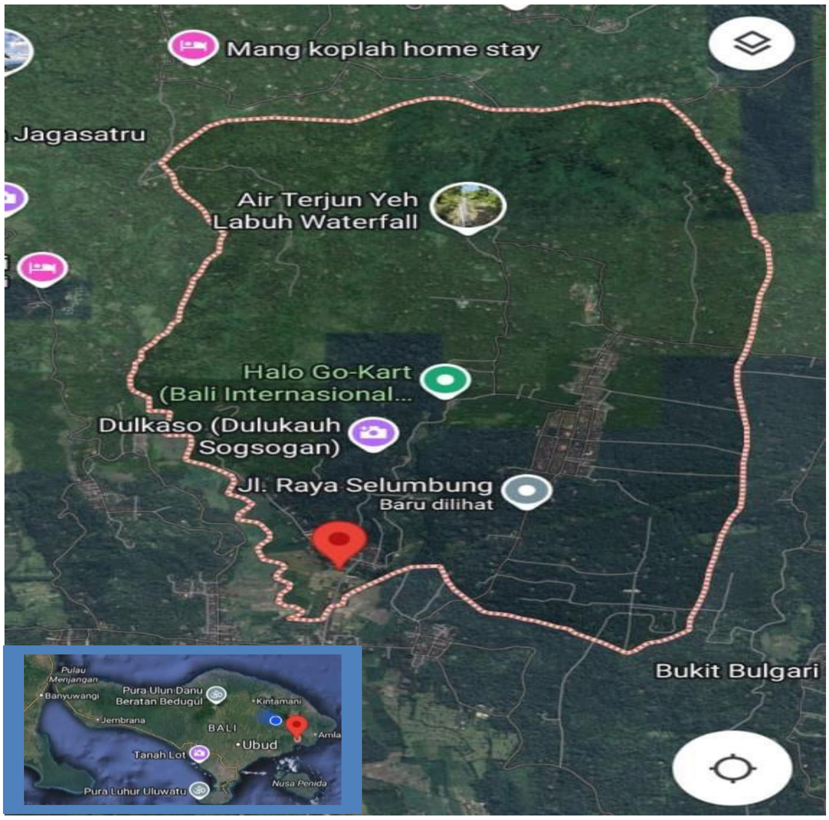

Figure four point one shows the research location map of Selumbung Village.

Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

Data Sources

Two types of data were collected, primary data and secondary data. Primary data consisted of direct field observations and laboratory analysis results. Secondary data included information previously compiled by institutions or individuals and used as supporting data.

Primary data collected in the field included land use, soil type, slope category, and soil sampling points. Laboratory analysis provided values of cation exchange capacity in milliequivalents per one hundred grams, base saturation in percent, pH in water, organic carbon in percent, total nitrogen in percent, phosphorus in the form of P two O five in parts per million, and potassium in the form of K two O in parts per million.

Research Variables

The research variables consisted of field based land characteristics and laboratory based soil chemical properties. Field observations included soil type, land use, slope, and general land characteristics. Laboratory analyses measured total nitrogen, P two O five, K two O, cation exchange capacity, base saturation, and organic carbon.

Research Materials

The materials used included Worldview satellite imagery for Manggis District in the year two thousand twenty two, a Subak paddy field map with a scale of one to twenty five thousand, a semi detailed soil map from the Soil and Agroclimate Research Center with a scale of one to fifty thousand, and the DEMNAS twenty eighteen slope map with eight meter resolution. Soil samples from the field and the chemical reagents used in soil analysis were also included among the research materials.

Research Instruments

The instruments used in this research included a global positioning system device, an Android mobile phone, an abney level, a hoe, a soil auger, a field knife, plastic sampling bags, a pH meter, a two millimeter sieve, measuring cylinders, volumetric pipettes, a suction bulb, digestion equipment, distillation apparatus, boiling flasks, test tubes, filter paper, an analytical balance, pipettes, an oven, a stopwatch, writing tools, a laptop computer, and the QGIS version three point two eight point five geographic information system software.

Research Procedures

The research procedure consisted of the following stages.

1. Literature Review

   This stage involved collecting secondary data from various sources such as topographic maps, Subak paddy field maps, semi detailed soil maps, and the DEMNAS two thousand eighteen slope map. Additional information was obtained from books, online sources, and direct visits to relevant institutions to gather general information about Manggis District and Selumbung Village.
2. Preliminary Survey

   The preliminary survey included a reconnaissance of the entire study area boundary to understand the condition of the land to be assessed. Interviews with farmers and Subak managers were also conducted to gather supporting information regarding land management practices.
3. Development of Homogeneous Land Unit Map

   Digital data processing was carried out to produce a land use map by cropping the base map according to the administrative boundary of Selumbung Village. This map was then overlaid with soil type data, slope data, and the paddy field land use map to generate homogeneous land units. QGIS version three point two eight point five was used for this mapping process.
4. Field Survey and Soil Sampling

   Field surveys were conducted to validate soil sampling points and observe physical site conditions. Soil samples were collected using purposive sampling at the tillage layer at a depth of zero to fifty centimeters. Disturbed and undisturbed samples were composited and prepared for laboratory analysis, which included the measurement of cation exchange capacity, base saturation, organic carbon, total potassium, total phosphorus, and pH.
5. Soil Preparation and Laboratory Analysis

   Laboratory analyses were conducted to determine cation exchange capacity using ammonium acetate one normal at pH seven, base saturation using ammonium acetate one normal at pH seven, organic carbon using the Walkley and Black method, total potassium using hydrochloric acid twenty five percent, total phosphorus using hydrochloric acid twenty five percent, and pH in water.

   The soil fertility status was assessed by comparing the results with the reference standards in the Technical Guidelines for Soil Fertility Evaluation published in 1995.

The classification used thirty combinations of soil chemical properties as presented in Table four point two.

6. Development of Soil Fertility Map
The soil fertility map was created to identify the distribution and boundaries of soil fertility across the Subak Blongyang paddy field area. Mapping was carried out using QGIS version three point two eight point five.
7. Soil Management Recommendations
Soil management recommendations were developed based on limiting factors identified from the soil fertility assessment. Each location received site specific recommendations to improve input efficiency and optimize soil management.

Data Analysis

Soil fertility evaluation was supported by both laboratory results and field observations. All soil analysis data were tabulated and processed to produce actual and potential soil quality maps for each homogeneous land unit. The soil fertility map was then integrated with the database to develop a geospatial soil fertility information system and to generate the soil management recommendation map.

RESULTS

General Condition of the Study Area and Land Characteristics

This research was conducted on several Homogeneous Land Units (HLU) in Selumbung Village, Manggis District, Karangasem Regency, which served as sampling locations for soil analyses as part of the WRI Project. Soil samples were collected using composite sampling within each HLU representing three land management systems in rice fields, namely conventional, organic, and semi-organic systems, characterized by diverse topography and soil types. The samples were analyzed in the laboratory to determine basic physical characteristics, including land slope, solum depth, and soil type, which form the basis for interpreting soil fertility levels and assessing the potential for sustainable rice field management in Selumbung.

Field observations revealed notable variation in environmental conditions across the study sites, particularly in land slope (0–45%), soil types (Alluvial and Regosol), and solum depth (25–50 cm). These variations reflect differences in physiography and land management practices that influence productivity and soil conservation strategies within each HLU. The general land characteristics are presented in Table 1.

Table 1. General Conditions and Land Characteristics in Selumbung Village, Manggis District, Karangasem

No	Code	Slope (%)	Soil Type	Land Use	Vegetation Condition	Solum Depth (cm)
1	HLU 1	25–45	Alluvial	Conventional Rice Field	No vegetation (post-harvest)	25
2	HLU 2	0–8	Alluvial	Conventional Rice Field	No vegetation (post-harvest)	35
3	HLU 3	25–45	Regosol	Conventional Rice Field	No vegetation (post-harvest)	30
4	HLU 4	0–8	Regosol	Conventional Rice Field	No vegetation (post-harvest)	32.5
5	HLU 5	0–8	Regosol	Organic Rice Field	No vegetation (post-harvest)	50
6	HLU 6	0–8	Regosol	Semi-Organic Rice Field	No vegetation (post-harvest)	35

Source: WRI Project Field Survey and Soil Laboratory Analysis, 2025.

The results in Table 5.1 indicate that each HLU in Selumbung Village has unique characteristics, reflecting the diversity of rice field ecosystems in the eastern agroecological zone of Bali. HLU 1 and HLU 3 exhibit the steepest slopes (25–45%), with Alluvial and Regosol soils that are more prone to erosion, necessitating more intensive soil conservation strategies. Conversely, HLU 2, 4, 5, and 6, characterized by flatter topography (0–8%), provide more stable conditions that support organic and semi-organic farming practices.

Differences in soil type also influence water-holding capacity and nutrient retention. Alluvial soils generally have finer textures and higher moisture-holding capacity, while Regosols are coarse-textured and typically low in organic matter. Solum depth, ranging from 25 to 50 cm, further affects root development and water availability. HLU 5, with the deepest solum (50 cm), has higher potential fertility compared to HLU 1 with only 25 cm of solum depth. Overall, these physical land characteristics directly influence production potential, input management, and soil conservation needs across the HLUs. Land with gentle slopes and deeper solum is more suitable for organic and semi-organic systems, while steeper lands with shallow solum require stricter conservation measures to maintain soil stability and productivity.

Soil Fertility Parameter Analysis

The results of soil sample analysis from Selumbung Subak, Manggis District, are presented in Table 5.2. The soil fertility parameters analyzed include Cation Exchange Capacity (CEC), Base Saturation (BS), soil organic carbon (C-organic), and total phosphorus (P-total) and potassium (K-total). The chemical properties of each HLU are shown in Table 2.

Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

Table 2. Chemical Properties of Soils in Selumbung Village, Manggis District, Karangasem Regency

No	HLU	CEC (me/100 g)	BS (%)	C-Org (%)	P-Total (mg/100 g)	K-Total (mg/100 g)
1.	HLU I	27.92 (H)	81.89 (VH)	1.29 (L)	1471.917 (VH)	72.839 (H)
2.	HLU II	28.06 (H)	83.72 (VH)	1.27 (L)	1470.808 (VH)	72.452 (H)
3.	HLU III	28.07 (H)	85.04 (VH)	1.29 (L)	1341.183 (VH)	72.472 (H)
4.	HLU IV	21.87 (M)	99.01 (VH)	2.11 (M)	1220.774 (VH)	70.368 (H)
5.	HLU V	26.45 (H)	83.87 (VH)	0.83 (L)	1400.145 (VH)	69.562 (M)
6.	HLU VI	23.33 (M)	97.09 (VH)	2.21 (M)	2228.999 (VH)	75.454 (H)

Notes: VH = Very High; H = High; M = Moderate; L = Low

Based on the analysis displayed in Table 5.2, the soil chemical characteristics in Selumbung Subak show variation among HLUs in terms of CEC, base saturation, organic carbon content, and macronutrients P and K.

HLU I exhibits high CEC (27.92 me/100 g) and very high BS (81.89%). Organic carbon content is low (1.29%), while P-total and K-total are very high. This indicates a soil rich in nutrients but limited by low organic matter, which may reduce biological activity without regular organic amendments.

HLU II has a similar pattern, with high CEC and very high BS, low organic carbon, and high P and K availability. This suggests intensive fertilizer inputs typical of conventional rice farming.

HLU III also shows high CEC, very high BS, low organic carbon, and very high P and K, comparable to HLU I and II. This implies homogeneity in land management and nutrient inputs across these sites.

HLU IV differs from the first three, with moderate CEC (21.87 me/100 g), very high BS, moderate C-organic (2.11%), and very high P and K. Higher organic carbon indicates better organic matter decomposition or improved land management.

HLU V has high CEC and very high BS but very low organic carbon. Although rich in P and K, low organic matter limits its biological fertility, as commonly found in newly converted organic fields.

HLU VI shows moderate CEC, very high BS, higher organic carbon (2.21%), and the highest P-total concentration. This combination suggests superior balance of chemical and organic fertility across sites.

Overall, soils in Selumbung exhibit high CEC and BS with abundant P and K, indicating strong chemical fertility. However, low organic carbon in several HLUs highlights the need for continuous organic matter inputs to maintain long-term soil health and nutrient balance.

Evaluation of Soil Fertility Status

The fertility status of soils in Selumbung Village was evaluated through two main stages. The first stage consisted of laboratory analysis of key chemical parameters, specifically cation exchange capacity (CEC), base saturation (BS), organic carbon content, total phosphorus, and total potassium. The second stage involved the classification of soil fertility levels using the established Soil Fertility Assessment Criteria. The results of this evaluation are presented in Table 3.

Table 3. Soil Fertility Status in Selumbung Village, Manggis District, Karangasem Regency

No	HLU	CEC	BS	C-Org	P-Total	K-Total	Fertility Status
1	HLU I	27.92 (H)	81.89 (VH)	1.29 (L)	1471.917 (VH)	72.839 (H)	Moderate
2	HLU II	28.06 (H)	83.72 (VH)	1.27 (L)	1470.808 (VH)	72.452 (H)	High
3	HLU III	28.07 (H)	85.04 (VH)	1.29 (L)	1341.183 (VH)	72.472 (H)	High
4	HLU IV	21.87 (M)	99.01 (VH)	2.11 (M)	1220.774 (VH)	70.368 (H)	High
5	HLU V	26.45 (H)	83.87 (VH)	0.83 (L)	1400.145 (VH)	69.562 (M)	Moderate
6	HLU VI	23.33 (M)	97.09 (VH)	2.21 (M)	2228.999 (VH)	75.454 (H)	High

Note: ST = Very High; T = High; S = Moderate; R = Low

The results indicate that HLU I and HLU V fall under the **moderate** fertility category, while HLU II, III, IV, and VI are classified as **high fertility**.

Moderate fertility in HLU I is attributed to low organic carbon, despite high CEC, BS, and nutrient availability. Organic matter deficiency limits soil biological activity and nutrient retention.

HLU II, III, IV, and VI show high fertility supported by strong chemical properties. Higher organic carbon in HLU IV and VI further enhances soil structure, water-holding capacity, and microbial activity.

HLU V, although high in chemical nutrients, has low organic carbon, reducing its overall fertility rating.

Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

These variations reflect differences in land management and inherent soil conditions. HLUs with high fertility tend to have balanced topography and better organic matter accumulation, while moderate-fertility HLUs require improvement, especially through organic matter enrichment.

Based on these findings, the following management recommendations are proposed:

1) **For HLUs with moderate fertility (HLU I and V):**

Increase organic matter inputs through compost or manure.

Apply soil conservation practices to reduce erosion and improve water retention.

2) **For HLUs with high fertility (HLU II, III, IV, VI)**

Maintain long-term fertility through balanced fertilization, crop residue management, and proper crop rotation.

This evaluation provides a strong foundation for land-use planning and sustainable agricultural productivity in Selumbung Subak.

Soil Fertility Status Map

The soil fertility status map is one of the outputs of this research, illustrating the spatial distribution of soil fertility levels along with explanatory attributes related to soil fertility parameters. The map visually represents fertility conditions in Selumbung Subak, Manggis District. In the map, yellow polygons indicate areas with **moderate fertility status**. The soil fertility map of Selumbung Subak is presented in **Figure 1**.

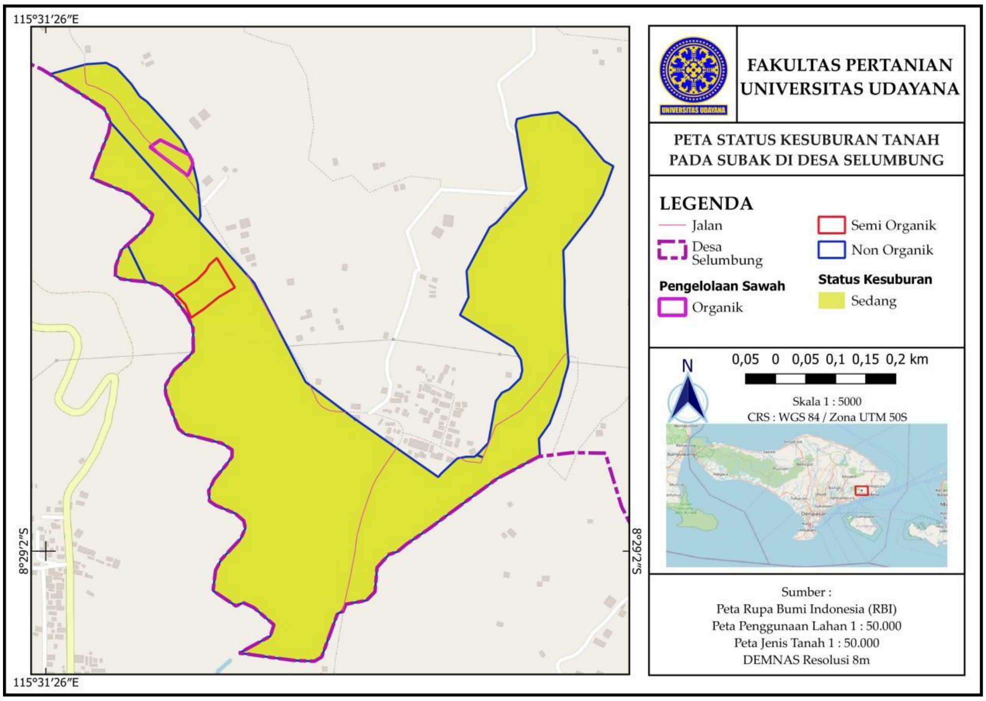

Figure 1: Soil Fertility Status Map of Selumbung Village, Manggis District

DISCUSSION

This study aimed to evaluate the soil fertility status in Selumbung Village, Manggis District, Karangasem Regency, as a basis for developing recommendations for sustainable land management. The approach employed integrated spatial analysis using Geographic Information Systems (GIS) with laboratory assessments of key chemical parameters, namely Cation Exchange Capacity (CEC), Base Saturation (BS), organic carbon (C-organic), total phosphorus (total P), and total potassium (total K). These five parameters serve as important indicators because they represent the soil's ability to store, exchange, and supply essential nutrients to plants, thereby directly influencing agricultural productivity and long-term sustainability in the area.

Field observations showed that the land in the Selumbung Subak exhibits considerable variation in topography and soil types, with slopes ranging from 0–45%, dominated by Regosol and Alluvial soils. These physiographic variations significantly affect soil fertility dynamics and agricultural productivity. Regosols generally have coarse textures, low organic matter, and limited water and nutrient retention capacities, while Alluvial soils display better fertility due to their fine mineral-rich deposits. Soil depth ranges from 25–50 cm, and lands with slopes above 25% face a higher risk of nutrient loss through erosion and surface runoff. Therefore, in homogeneous land units (HLUs) located in sloping areas, soil conservation techniques such as terracing and cover crops are essential to maintain soil stability and fertility.

Evaluation of Soil Fertility Status in Selumbung Village, Manggis District

The dominant vegetation in Selumbung Village consists of paddy fields managed under intensive agricultural systems throughout the year. However, high cultivation intensity and low organic inputs have reduced soil organic matter content. This condition aligns with the findings of Susila et al. (2024), who reported declining organic matter levels in Subak lands in Bali due to increased planting frequency and chemical fertilizer use. Thus, management strategies are needed to balance high productivity with long-term soil fertility, such as adopting organic or semi-organic farming systems.

Chemical soil analysis showed that the CEC values ranged from 21.87–28.07 me/100 g, falling into the medium to high categories. These values indicate a relatively good capacity for nutrient retention and exchange. High CEC is typically associated with adequate clay and organic matter content, although in several HLUs (such as HLU I–III), the organic matter content remains low. This indicates that clay minerals such as montmorillonite or illite play a role in increasing cation exchange capacity (Trigunasih & Wiguna, 2022). Base Saturation (BS) values across all HLUs were classified as very high (81–99%), suggesting that most soil colloids are saturated with base cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. This condition reflects good soil chemical fertility and near-neutral pH, which facilitates optimal nutrient availability. However, if high BS is not accompanied by increased organic matter, soil aggregate stability may decline and nutrient leaching risks may increase in the long term (Amalia et al., 2024).

The organic carbon content in Selumbung Village ranges from 0.83–2.21%, indicating that most HLUs fall into the low to medium categories. Low organic matter content results from intensive farming systems, straw burning, and limited use of organic fertilizers. Insufficient organic matter directly affects microbial activity, nitrogen availability, water retention, and soil structure stability. HLUs IV and VI have higher organic carbon content (approximately 2.11–2.21%), indicating better land management through the application of manure or semi-organic systems. This condition positively influences porosity and nutrient absorption efficiency. Increasing organic matter through straw incorporation, green manure, compost, or biochar should be prioritized, in line with Niki et al. (2022), who stated that organic matter levels above 2% can enhance CEC and fertilizer efficiency in paddy soils.

Meanwhile, macronutrient levels such as phosphorus (P) and potassium (K) were high, with total P ranging from 1,220–2,229 mg/100 g and total K from 69–75 mg/100 g. High phosphorus levels are likely due to the accumulation of inorganic fertilizer residues from intensive fertilization. However, P uptake efficiency may decrease in soils with low organic matter because P is easily fixed by Ca^{2+} or Fe^{3+} ions (Johan et al., 2021). High potassium levels are also important for increasing plant tolerance to abiotic stress and improving crop quality. Nevertheless, the balance between K, Mg, and Ca must be maintained to avoid nutrient antagonism (Xie et al., 2021). Overall, high P and K contents indicate good chemical fertility potential, but balanced fertilizer management is required to prevent excessive nutrient accumulation.

Based on parameter integration, soil fertility status in Selumbung Village ranges from medium to high. Four HLUs (II, III, IV, and VI) fall into the high category, while two HLUs (I and V) are classified as medium. This variation is closely related to the combination of organic matter content and topographic conditions. HLUs with high fertility have adequate organic matter, high CEC and BS values, and abundant P and K nutrients. Conversely, HLUs with medium fertility are typically found in undulating areas with low organic matter. This pattern indicates that organic matter content is the primary limiting factor in maintaining soil fertility. These findings are consistent with Simatupang et al. (2021), who reported that decreasing organic matter reduces CEC and fertilizer efficiency in paddy soils in Bali. Similar results were reported by Susila et al. (2024), who found that agricultural intensification without continuous organic matter inputs reduces soil productivity and degrades soil structure in Subak systems in Karangasem. Thus, increasing organic matter through straw return and organic fertilizer application is essential to sustain long-term soil fertility in Selumbung Village.

The use of Geographic Information Systems (GIS) in this study played a crucial role in analyzing the spatial distribution of soil fertility across HLUs. Mapping results showed that highly fertile areas were concentrated on flat to gently sloping land, while medium fertility areas were generally located on sloping land with high erosion potential. GIS-based spatial analysis enables accurate visualization of variations in fertility parameters such as organic matter, total P, total K, and CEC, facilitating more efficient land management zoning. This spatial integration supports site-specific management, allowing farmers to adjust fertilizer dosages, irrigation systems, and crop types based on the fertility level of each land unit. GIS-based approaches have been shown to improve fertilization efficiency and crop productivity, as reported by Simatupang et al. (2021), who found that GIS-based soil fertility mapping optimizes nutrient distribution and minimizes soil degradation in intensive paddy fields in Bali.

Based on the evaluation, soil fertility conditions in Selumbung Village vary across land units. Most areas exhibit high fertility status, while others fall into the medium category. This variation reflects differences in biophysical characteristics, soil management practices, and cultivation intensity among HLUs. High fertility areas are generally found on flat to gently undulating land with relatively good organic matter content, while medium fertility areas are located on sloping terrain with low organic matter. This pattern illustrates the significant influence of topography and organic management on soil fertility (Susila et al., 2024).

Lands with high fertility status (HLUs II, III, IV, and VI) are characterized by high to very high CEC and BS values, as well as abundant macronutrient availability such as P and K. These conditions indicate a strong chemical capacity to support plant growth.

Maintaining fertility is essential to prevent degradation due to nutrient leaching or declining organic matter. Recommended efforts include balanced fertilization with organic and inorganic inputs, returning crop residues to the soil, and implementing crop rotation and diversification to maintain nutrient balance (Puja & Atmaja, 2018). Efficient irrigation management is also necessary to reduce nutrient losses, particularly in paddy fields with high cropping intensity (Trigunasih et al., 2017). Moreover, soil conservation on sloping lands through terracing or cover crops plays an important role in maintaining topsoil stability and controlling erosion (Suriadikusumah et al., 2020).

Conversely, lands with medium fertility status (HLUs I and V) have relatively good CEC and BS values but low organic carbon content. Low organic matter limits soil biological activity and reduces nutrient retention capacity (Wibowo & Kasno, 2021). Management should focus on increasing organic matter through regular application of manure, green manure, and compost. Biofertilizers containing phosphate-solubilizing and nitrogen-fixing microbes are also recommended to improve nutrient uptake efficiency (Lovitna et al., 2021). Conservation-based cropping systems such as intercropping and legume rotation effectively improve soil structure and enhance natural nitrogen addition (Trigunasih & Dibia, 2019). Water management in sloping areas is needed to prevent nutrient leaching, while regular monitoring of soil pH is essential to ensure optimal nutrient availability (Ferry et al., 2024). Increasing organic matter represents a strategic step to elevate fertility status from medium to high because it enhances CEC, porosity, and soil structural stability (Trigunasih & Wiguna, 2022).

Overall, paddy soils in Selumbung Village have strong potential for development under organic-based sustainable agriculture. The main challenges include low organic matter content and varied topographic conditions. Therefore, strengthening the Subak system through organic fertilizer application, efficient water management, and soil conservation is key to maintaining long-term fertility. This study also emphasizes the importance of regular GIS-based soil fertility monitoring to detect spatial and temporal changes resulting from intensive agricultural activities. With scientific approaches and adaptive management, the Subak system is expected to maintain its capacity as a productive and environmentally friendly model of sustainable agriculture unique to Bali.

CONCLUSION

The findings of this study demonstrate that the overall soil fertility status in Selumbung Village, Manggis District, Karangasem Regency, ranges from moderate to high. Laboratory analysis revealed that the soils possess cation exchange capacity (CEC) values between 21.87 and 28.07 me/100 g, classified as moderate to high, accompanied by very high base saturation levels (81.89–99.01%). Macro-nutrient availability, particularly total phosphorus (P-total) and total potassium (K-total), was categorized as high to very high, although soil organic carbon remained low to moderate. Based on these combined parameters, four homogeneous land units (SLH II, III, IV, and VI) exhibited high fertility status, whereas SLH I and V were classified as moderately fertile. These results indicate that the soils in Selumbung Village have strong productive potential but still require improvement in organic matter management.

The study also identified key limiting factors that influence soil fertility across the area. Chemically, low organic matter content reduces microbial activity and limits nutrient uptake efficiency. Physically, sandy-dominated soil texture decreases the soil's capacity to retain water and nutrients. Biologically, the limited input of organic residues suppresses soil organism activity and slows nutrient cycling. The interaction among these chemical, physical, and biological constraints significantly affects the soil's ability to maintain and enhance its fertility.

The recommended land management strategies to improve soil fertility include the application of balanced fertilization through the combined use of organic amendments such as manure, compost, and green manure, along with inorganic NPK fertilizers that are adjusted according to soil test results. In addition, soil and water conservation practices should be implemented, including terracing on sloped land, the use of cover crops, and improved surface water management to minimize erosion and nutrient loss. The adoption of soil fertility maps supported by Geographic Information System (GIS) technology is essential for promoting site-specific and sustainable land management in Selumbung Village.

ADVICE

For improving soil quality in Selumbung Village, it is recommended that farmers consistently increase soil organic matter by applying manure, compost, green manure, and crop residues on a regular basis because these inputs are effective in enhancing soil structure, increasing cation exchange capacity, and stimulating soil microbial activity. For fertilizer management, balanced and site-specific fertilization should be carried out by combining organic inputs with inorganic NPK fertilizers according to soil test results in each homogeneous land unit so that nutrient uptake becomes more efficient and soil fertility can be maintained in the long term. For land conservation, areas with moderate to steep slopes should apply terracing, drainage channels, and cover crops in order to reduce erosion, maintain soil moisture, and minimize nutrient loss.

For long-term sustainability, farmers and local institutions are encouraged to adopt environmentally friendly agricultural practices such as crop rotation, crop and livestock integration, and the application of biofertilizers since these approaches help maintain nutrient balance and support continuous land productivity. For land-use planning, the use of Geographic Information System or GIS technology should be further developed to support soil fertility mapping, conservation planning, and decision making at both the farmer and regional levels. For advancing scientific understanding, further studies are recommended to include a deeper analysis of soil biological characteristics, particularly microbial populations and enzyme activity, so that the interaction among chemical, physical, and biological soil factors can be explained more comprehensively.

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