ASIAN JOURNAL OF AGRICULTURE
Volume 10, Number 1, June 2026
Pages: 9

E-ISSN: 2580-4537
https://doi.org/10.13057/asianjagric/g100172

Soil fertility evaluation and crop development in Kubutambahan Sub-district, Buleleng District, Indonesia

MADE SRI SUMARNIASIH[1,♥], PUTU PERDANA KUSUMA WIGUNA[1], PUTU OKI BIMANTARA[1], I NENGAH KARNATA[2]

[1]Department of Agroecotechnology, Faculty of Agriculture, Universitas Udayana. Jl. PB. Sudirman, Denpasar 80231, Bali, Indonesia. Tel.: +62-361-702801, Fax.: +62-361-703602, ♥email: sumarniasih@unud.ac.id

[2]Department of Agroecotechnology, Faculty of Sains and Technology, Universitas Tabanan. Jl. Wagimin No. 8, Kediri, Tabanan, Bali 82121, Indonesia

Manuscript received: 28 July 2025. Revision accepted: 9 June 2026.

Abstract. *Sumarniasih MS, Wiguna PPK, Bimantara PO, Karnata IN. 2026. Soil fertility evaluation and crop development in Kubutambahan Sub-district, Buleleng District, Indonesia. Asian J Agric 10 (1): g100172. https://doi.org/10.13057/asianjagric/g100172.* The productivity of agricultural land is strongly influenced by soil fertility, yet detailed and spatially explicit assessments remain limited in many parts of Bali despite its diverse agroecosystems. This study assessed soil fertility in Kubutambahan Sub-district, Buleleng District, Bali, Indonesia, by delineating Homogeneous Land Units (HLUs) using GIS-based spatial analysis and conducting representative soil sampling. Seven HLUs were analyzed for key soil chemical properties, including organic C, total P_2O_5, total K_2O, Cation Exchange Capacity (CEC), Base Saturation (BS), and pH, and fertility status was determined following national evaluation guidelines using the principle of the most limiting factor. The results indicate that soil fertility across the district is predominantly low to moderate, with organic carbon levels (1.33-1.71%) consistently identified as the most critical limiting factor. Approximately 68.2% of the area (8,380 ha) was classified as low fertility, while the remaining 31.8% (3,908 ha) exhibited medium fertility. Low organic matter, low CEC, and, in some areas, very low BS were the primary causes of reduced fertility, despite generally adequate levels of phosphorus and potassium. Statistical analysis showed that organic carbon was significantly correlated with CEC ($r = 0.49$, $p < 0.05$) and base saturation ($r = 0.65$, $p < 0.01$), confirming its key role as a controlling factor of soil fertility. These findings highlight organic carbon as the primary limiting factor and emphasize the need for HLU-based, site-specific management strategies focused on organic matter restoration to enhance soil fertility and agricultural productivity in the study area. This study provides the first spatially explicit soil fertility assessment at the sub-district scale in Kubutambahan and highlights the need for HLU-based, site-specific management strategies emphasizing organic matter restoration to support sustainable agricultural productivity.

Keywords: Ecological resilience, Homogeneous Land Units, nutrient inefficiency, soil organic carbon, sustainable land management

INTRODUCTION

The success of crop cultivation is fundamentally determined by soil fertility, as it reflects the capacity of soils to supply essential nutrients required for plant growth and productivity (Sopialena et al. 2017; Anim et al. 2025; Karabayev et al. 2025). Water availability, topography, and soil depth also influence agricultural performance. However, soil fertility remains the most critical determinant for sustaining yields across different farming systems. Soils with low nutrient availability typically constrain crop development, whereas fertile soils enable consistent and long-term productivity (Sofo et al. 2021; Dossouhoui et al. 2025; Topa et al. 2025). Soils differ widely in their nutrient content and nutrient-supplying capacity depending on local conditions. Therefore, fertility assessments must be site-specific and tailored to individual agroecosystems (Bünemann et al. 2018; Kome et al. 2019). Based on topographic data from the RBI map, Kubutambahan Sub-district exhibits diverse topographic and land-use conditions, with slopes ranging from 8% to 40%. The area includes soil types such as regosols and latosols distributed across forests, rice fields, mixed plantations, and scrublands, where farmers' management decisions depend on accurate evaluations of soil quality and constraints. Soil fertility evaluation serves as a fundamental tool to identify limiting nutrients and to guide appropriate interventions that improve soil management. In many agricultural regions, fertility assessments not only provide baseline information on nutrient stocks but also help design strategies for long-term sustainability, especially under pressures of land degradation and climate variability (Khadka et al. 2016; Suwardi 2019; Kuunya et al. 2026). Fertility evaluation in Indonesia has long been recognized as an essential step toward sustainable agriculture, particularly in areas experiencing nutrient depletion due to intensive cropping. Across the Indonesian archipelago, site-based evaluations allow stakeholders to understand soil variability and to implement management practices adapted to local biophysical and socio-economic contexts.

In Bali, Indonesia, research related to soil fertility and land management has generally focused on specific agroecosystems or districts. For instance, Sumarniasih and Antara (2021) examined strategies for sustainable dryland management in Buleleng District, while Trigunasih and Wiguna (2020) analyzed land suitability and conservation planning in the Ho watershed of Tabanan District. Another study by Trigunasih and Wiguna (2022) assessed the fertility status of *subak* rice fields in Denpasar City, reflecting the importance of traditional irrigation systems for soil and crop productivity. These studies provide valuable insights into localized soil fertility and land use, but their coverage remains limited in scope. Despite the agricultural importance of Bali, many districts have not been systematically evaluated, leaving gaps in evidence-based recommendations for land and soil management.

One such underexplored region is Kubutambahan Sub-district, located in Buleleng District. With an area of 118.24 km², Kubutambahan encompasses diverse land uses ranging from irrigated rice fields to plantations and mixed horticultural systems. Agriculture is the dominant livelihood source for local communities. Agricultural production in Kubutambahan includes staple crops, horticulture, and plantation commodities. These consist of paddy (9,021 tons), maize (4,448 tons), root crops (2,980 tons), as well as fruits and plantation products such as mango (9,893 tons), coconut (14,697 tons), clove (9,546 tons), and coffee (7,689 tons) (Central Bureau of Statistics of Buleleng District 2023, 2025). These figures demonstrate that agriculture remains a dominant livelihood source. However, crop productivity still requires improvement, as yields vary widely across the landscape. Unlike other districts in Bali where fertility assessments or land evaluations have been conducted, Kubutambahan has not undergone systematic soil fertility mapping or nutrient analysis.

Based on the identified gaps, this study hypothesizes that soil fertility variation in Kubutambahan is primarily controlled by Soil Organic Carbon (SOC), which regulates key soil properties such as Cation Exchange Capacity (CEC) and Base Saturation (BS) across different Homogeneous Land Units (HLUs). It is further hypothesized that, despite the presence of relatively high levels of mineral nutrients (P_2O_5 and K_2O), low SOC limits effective nutrient retention and availability, resulting in spatially heterogeneous but structurally constrained soil fertility. Therefore, integrating HLU-based spatial analysis with SOC dynamics provides a more accurate framework for assessing soil fertility patterns and identifying site-specific management strategies.

Therefore, this study aims to (i) evaluate the soil fertility status of Kubutambahan Sub-district, (ii) identify the key limiting factors that constrain land productivity, and (iii) propose site-specific management strategies to improve fertility and support sustainable agricultural development. This study integrates soil chemical analyses with spatial delineation of homogeneous land units. It provides the first comprehensive fertility evaluation for this district. The findings provide direct recommendations for farmers. They also offer strategic insights for policymakers and development planners. The novelty of this research lies in its focus on an agriculturally significant but previously overlooked district, thereby contributing to more balanced agricultural development strategies and sustainable land use planning across Bali.

MATERIALS AND METHODS

Research location and climate

The research was conducted in Kubutambahan Sub-district of Buleleng District, Bali Province, Indonesia, spanning from September 2021 to January 2022. Kubutambahan Sub-district covers an area of 118.24 km^2 (Central Bureau of Statistics of Buleleng District 2023). Climatically, the area is characterized by a tropical monsoon pattern with two distinct seasons: a wet season (October-April) and a dry season (May-September). Northern Bali, including Kubutambahan, typically receives lower annual rainfall compared to the southern parts of the island, resulting in seasonal water limitations (drought stress) that significantly influence soil properties, SOC decomposition rates, and agricultural practices, particularly in non-irrigated HLUs. The map of the research location is shown in Figure 1.

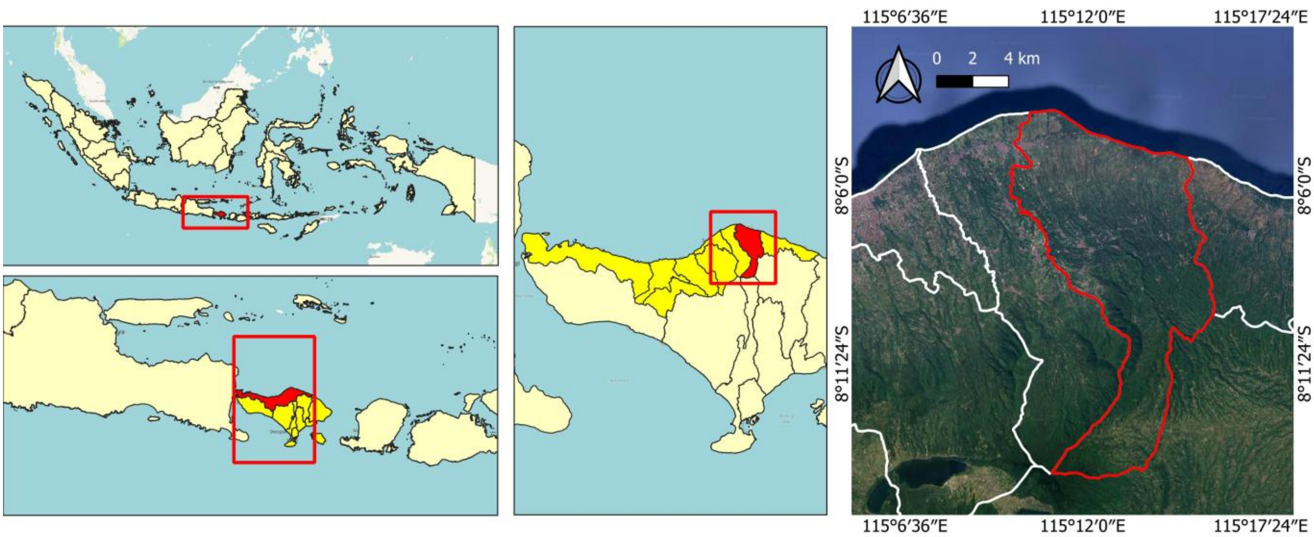

Figure 1. Research location in Kubutambahan Sub-district, Buleleng, Bali, Indonesia

Procedures for Homogeneous Land Unit (HLU) delineation and sampling

Soil fertility status was evaluated following the Technical Guidelines for Soil Fertility Evaluation issued by the Indonesian Soil Research Institute (Soil Research Center 1995). Homogeneous Land Units (HLUs) were delineated using GIS tools by overlaying land use, slope, and soil type maps. Seven HLUs were selected to represent the district's varied agroecosystems. Within each HLU, five subsamples were collected using an auger at random points within the 0-20 cm topsoil layer, then thoroughly mixed to form one composite sample per unit. This approach was designed to capture spatial variability across the district. However, the limited number of samples (n = 7) may reduce the robustness of the correlation analysis and is acknowledged as a study limitation.

Soil samples were analyzed at the Soil Laboratory, Faculty of Agriculture, Udayana University. The parameters measured included Organic C, total P_2O_5 and total K_2O, Cation Exchange Capacity (CEC), Base Saturation (BS), soil pH, and soil texture. Standardized and widely applied methods were used: the Walkley and Black method for Organic C (Enang et al. 2018), 25% HCl extraction for P and K (Dermawan et al. 2024), the extraction method for CEC (Purnamasari et al. 2021), NH4OAc 1N pH 7 for BS (Iticha et al. 2022), a 1:5 soil-water suspension for pH (Kargas et al. 2022), and the pipette method for soil texture (Guan et al. 2023).

The analytical results were compared with the classification criteria provided by the Indonesian Soil Research Institute (Table 1). Soil fertility status was determined by integrating the values of CEC, BS, Organic C, P, K, and pH according to the national guidelines (Table 3). The final fertility status for each HLU was determined by the principle of the most limiting factor, meaning the lowest classification among the critical parameters (typically Organic C, CEC, or BS dictates the overall fertility class. This evaluation framework is intended to guide general soil management and long-term sustainability across the district. However, the identified constraints (e.g., low Organic C and low B) serve as a scientific foundation for tailoring nutrient management and fertilizer amendments to meet the specific requirements of major local crops.

Soil fertility status was evaluated following the Technical Guidelines for Soil Fertility Evaluation issued by the Indonesian Soil Research Institute (Soil Research Center 1995). Homogeneous Land Units (HLUs) were delineated using QGIS software by overlaying three primary data layers: land use, slope (derived from DEM), and soil type maps. This spatial procedure allowed the categorization of the complex landscape into seven (7) distinct, uniform agroecosystems. These HLUs were strategically selected not as a statistically exhaustive sample for geostatistical extrapolation, but to represent the maximum observed spatial heterogeneity based on dominant land use and environmental factors within the sub-district.

Within each selected HLU, five subsamples were collected using an auger at random points within the 0-20 cm topsoil layer, then thoroughly mixed to form one composite sample per unit (n = 7 composite samples in total). This method-consistent with national guidelines for baseline soil fertility evaluation-was designed to capture the general mean fertility status within each defined HLU.

We acknowledge that due to the limited number of composite samples (n = 7) and the single-season sampling (conducted during the transition from the wet to the dry season), the results primarily provide a critical baseline status, representative of the defined HLUs only. Broad generalization across the entire district and quantitative spatial variability analysis should be approached with caution. The methodological novelty rests on the GIS-based spatial delineation of HLUs, which provides an actionable framework for site-specific management, justifying the subsequent recommendations. This limitation underscores the need for future multi-seasonal studies and increased sample density (e.g., integrating Remote Sensing data or geostatistical methods like Kriging) for more robust analysis and extrapolation.

The analytical results were compared with the classification criteria provided by the Indonesian Soil Research Institute. Soil fertility status was determined by integrating the values of CEC, BS, Organic C, P_2O_5, K_2O, and pH according to the national guidelines as described in Table 1. The criteria for determining soil fertility status based on combined soil chemical properties are provided in Table 2. This framework allowed each HLU to be classified into fertility levels ranging from very low to high. Pearson correlation analysis was applied to examine relationships among soil chemical properties. Correlation strength was expressed using correlation coefficients (r), and statistical significance was evaluated at $p < 0.05$ and $p < 0.01$. A schematic of the research process is presented in Figure 2.

Table 1. Criteria for assessment of soil chemical properties

Soil properties	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
Organic C (%)	< 1.00	1.00-2.00	2.01-3.00	3.01-5.00	> 5.00
Total P_2O_5 (mg/100g)	< 10	10-20	21-40	41-60	> 60
Total K_2O (mg/100g)	< 10	10-20	21-40	41-60	> 60
CEC (me/100g)	< 5	5-16	17-24	25-40	> 40
BS (%)	< 20	20-35	36-50	51-70	> 70
pH	4.5-5.5 (acidic)	5.6-6.5 slightly acidic)	6.6-7.5 (neutral)	7.6-8.5 (slightly alkaline)	> 8.5 (alkaline)

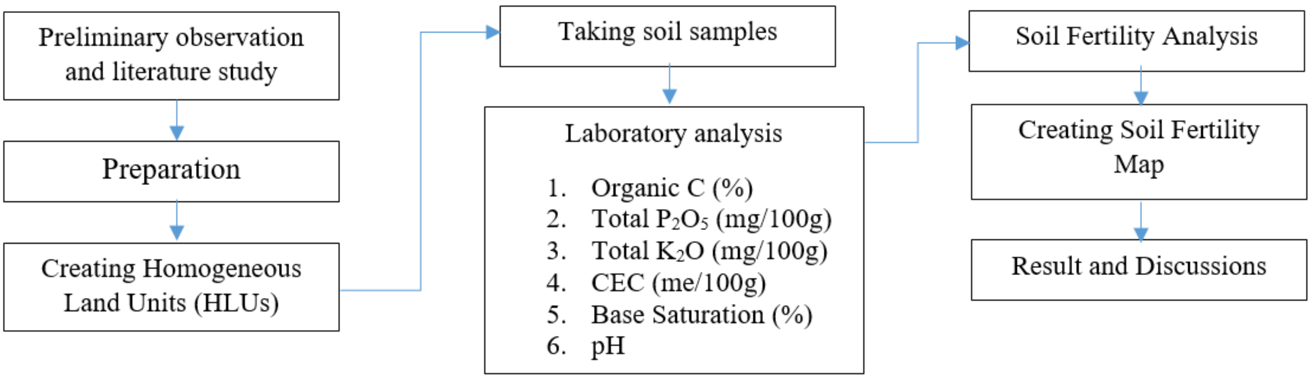

Figure 2. Workflow from spatial delineation of HLUs to soil fertility evaluation

Table 2. Determination of soil fertility status based on combined soil chemical properties

Cation Exchange Capacity (CEC)	Base Saturation (BS)	P_2O_5, K_2O, Organic C	Soil fertility status
H	H	≥ 2 H without L	High
H	H	≥ 2 H with L	Medium
H	H	≥ 2 M without L	High
H	H	≥ 2 M with L	Medium
H	H	H > M > L	Medium
H	H	≥ 2 L with H	Medium
H	H	≥ 2 L with M	Low
H	M	≥ 2 H without L	High
H	M	≥ 2 H with L	Medium
H	M	≥ 2 M	Medium
H	M	Other combinations	Low
H	L	≥ 2 H without L	Medium
H	L	≥ 2 H with L	Low
H	L	Other combinations	Low
M	H	≥ 2 H without L	Medium
M	H	≥ 2 M without L	Medium
M	H	Other combinations	Low
M	M	≥ 2 H with L	Medium
M	M	≥ 2 M without L	Medium
M	M	Other combinations	Low
M	L	3H	Medium
M	L	Other combinations	Low
L	H	≥ 2 H without L	Medium
L	H	≥ 2 H with L	Low
L	H	≥ 2 M without L	Medium
L	H	Other combinations	Low
L	M	≥ 2H without L	Medium
L	M	Other combinations	Low
L	L	All possible combinations	Low
VL	H, M, L	All possible combinations	Very low

Note: H: High, M: Medium, L: Low, VL: Very low

RESULTS AND DISCUSSION

A total of seven composite soil samples were collected, one from each Homogeneous Land Unit (HLU). Figure 3 presents the map of HLUs and sampling locations across Kubutambahan Sub-district, while Table 4 summarizes the characteristics of each HLU and their corresponding sampling points. Soil chemical analysis was conducted for each HLU, including texture, CEC, BS, pH, organic C, total phosphorus (P_2O_5), and total potassium (K_2O). The soil fertility status of each HLU was determined by classifying these parameters according to the criteria outlined in Table 1, then integrating the results following the procedure in Table 2.

The GIS-based spatial analysis successfully delineated seven Homogeneous Land Units (HLUs) (n = 7), representing the primary land use and topographic variability across the Kubutambahan Sub-district. Figure 3 presents the map of HLU and sampling locations, while Table 3 summarizes the characteristics of each HLU, including soil type (Regosol and Latosol), slope, and corresponding land use. Soil chemical analysis, encompassing texture, Cation Exchange Capacity (CEC), Base Saturation (BS), pH, Organic C, P_2O_5, and total K_2O, was conducted for each composite sample.

The integrated assessment in Table 4 shows that soil fertility across the district is predominantly low to medium, with HLUs 1, 3, and 6 classified as low and HLUs 2, 4, 5, and 7 as medium. No areas were classified as high fertility. Spatially, the total area classified as low fertility was 8,380 ha (68.20%), dominating upland areas such as moorlands, non-irrigated croplands, and shrublands. The medium fertility areas (3,908 ha, 31.80%) were primarily concentrated in irrigated rice fields and forested zones, as shown in Figure 4.

The principle of the most limiting factor consistently identified organic C as the overriding constraint across all HLUs. Table 4 shows that Organic C levels ranged narrowly from 1.18% to 1.71%, firmly placing all HLUs in the low classification. The analysis of soil chemical properties revealed significant spatial heterogeneity linked to HLU texture and land use. Textural influence on CEC was observed, where clay-rich HLUs (2 and 7) exhibited higher CE (26.5 me/100g) compared to Silt Loam units (e.g., 3 and 6). Soil pH ranged from slightly acidic (6.53 in HLU 4) to neutral/slightly alkaline (7.52 in HLU 6), with Base Saturation (BS) showing wide variation, from very low (HLU 6) to very high (HLU 4). Despite the uniformly low overall fertility, P_2O_5 and total K_2O stocks were generally high to very high across most HLUs, indicating an accumulation of mineral inputs within the system.

The correlation matrix in Table 5 shows both positive and negative relationships among soil properties. CEC was moderately positively correlated with organic C ($r = 0.49$, $p < 0.05$) but negatively correlated with soil pH ($r = -0.75$, $p < 0.01$) and total K_2O ($r = -0.73$, $p < 0.01$). Base Saturation (BS) showed positive correlations with organic C ($r = 0.65$, $p < 0.01$) and total P_2O_5 ($r = 0.75$, $p < 0.01$), whereas it was negatively correlated with pH ($r = -0.49$, $p < 0.05$). Soil pH was negatively correlated with organic C ($r = -0.56$, $p < 0.05$) and positively correlated with total K_2O ($r = 0.32$, $p < 0.05$). The strongest positive relationship was observed between total P_2O_5 and total K_2O ($r = 0.83$, $p < 0.01$; $R^2 = 0.6878$), as illustrated in Figure 5.

The spatial analysis confirmed that the agricultural landscape of Kubutambahan is governed by site-specific fertility constraints, with low Soil Organic Carbon (SOC) acting as the primary limiting factor across 68.2% of the total area. This uniform low Organic C status is a critical ecological constraint, indicating a compromised soil buffering capacity, low water retention (especially vital for dryland HLUs), and severely reduced trophic resources necessary for sustaining soil microbial diversity and healthy nutrient cycling. For instance, the low fertility status of HLU 6 was exacerbated by very low BS (19.61%), demonstrating a severe inability to retain base cations, which directly impacts the resilience of the agroecosystem to nutrient leaching (Zhang et al. 2023; de Vries et al. 2024).

Table 3. Characteristics of HLUs in Kubutambahan Sub-district, Buleleng, Bali, Indonesia

HLU/ Samples	Slopes (%)	Land use	Soil type	Village
1	8-15	Scrubs	Humus regosol	Tambakan
2	25-40	Forests	Yellowish-brown latosol	Pakisan
3	15-25	Mixed plantations	Brownish regosol	Tunjung
4	25-40	Mixed plantations	Grayish brown regosol	Bila
5	8-15	Irrigated rice fields	Brownish regosol	Bukti
6	8-15	Non-irrigated croplands	Brownish regosol	Bukti
7	15-25	Mixed plantations	Brownish regosol	Mengening

Table 4. Soil fertility status by HLU, highlighting low SOC as the main limiting factor

HLU	Texture	CEC (me/ 100 g)	BS (%)	pH H_2O	Organic C (%)	Total P_2O_5 (mg/ 100g)	Total K_2O (mg/ 100g)	Soil fertility status
1.	Sandy clay loam	23.02 (M)	100.90 (VH)	7.16	1.67 (L)	28.16 (M)	277.89 (VH)	Low
2.	Clay	26.59 (H)	69.42 (H)	6.66	1.71 (L)	23.45 (M)	236.28 (VH)	Medium
3.	Silt loam	13.26 (L)	92.31 (VH)	6.94	1.59 (L)	118.63 (VH)	439.85 (VH)	Low
4.	Silt loam	24.4 (M)	180.53 (VH)	6.53	1.68 (L)	236.69 (VH)	483.76 (VH)	Medium
5.	Clay loam	26.24 (H)	48.69 (M)	6.62	1.33 (L)	22.75 (M)	304.6 (VH)	Medium
6.	Silt loam	10.36 (L)	19.61 (VL)	7.52	1.18 (L)	78.25 (VH)	466.37 (VH)	Low
7.	Clay	26.59 (H)	69.42 (H)	6.66	1.71 (L)	23.45 (M)	236.26 (VH)	Medium

Note: L: Low, M: Medium, H: High, VH: Very high

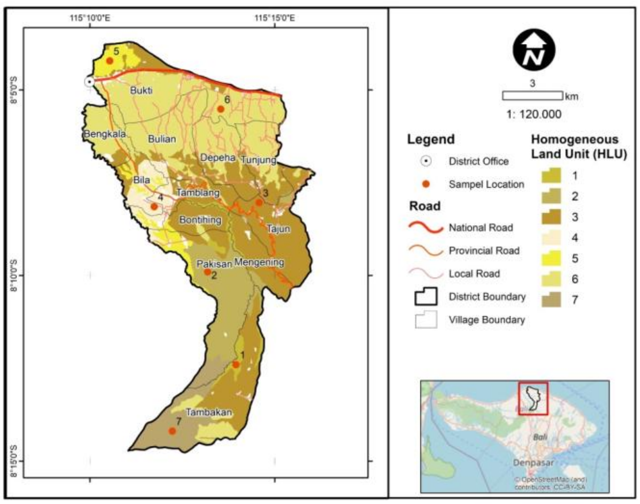

Figure 3. Spatial distribution of HLUs and soil sampling sites in Kubutambahan Sub-district, Buleleng, Bali, Indonesia

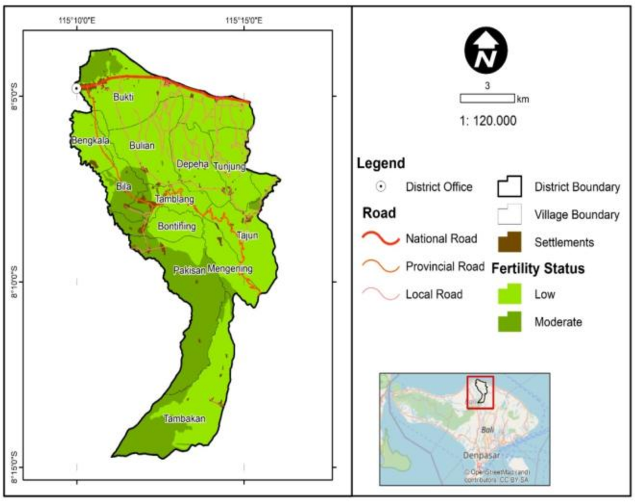

Figure 4. Soil fertility status in Kubutambahan Sub-district, Buleleng, Bali, Indonesia, with low fertility dominating upland areas

Table 5. Correlation matrix of soil properties, showing key relationships among fertility indicators

Parameters	CEC (me/100g)	BS (%)	pH H_2O	Organic C (%)	Total P_2O_5 (mg/100g)	Total K_2O (mg/100g)
CEC (me/ 100 g)	1					
BS (%)	0.25	1				
pH H_2O	-0.75	-0.49	1			
Organic C (%)	0.49	0.65	-0.56	1		
Total P_2O_5 (mg/100g)	-0.29	0.75	-0.15	0.12	1	
Total K_2O (mg/100g)	-0.73	0.30	0.32	-0.37	0.83	1

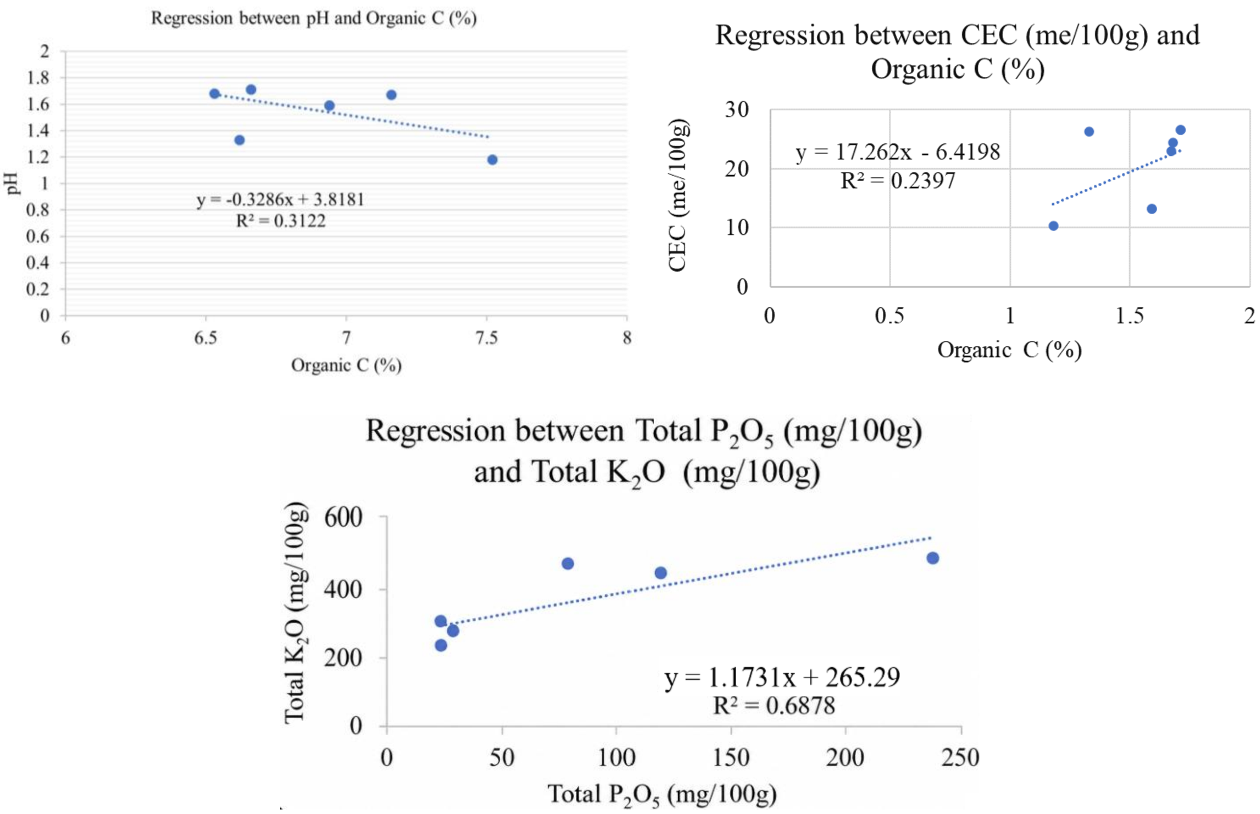

Figure 5. Regression relationships among soil properties, showing the strongest link between P_2O_5 and K_2O

Discussion

This finding extends beyond typical agronomic considerations, as the SOC deficit may influence agroecosystem resilience and soil functional capacity. The observed low SOC levels (all HLUs < 2%) are dynamically linked to high temperatures and rapid decomposition rates inherent in the tropical monsoon climate, a crucial factor for interpreting soil health. The significant positive correlations found between SOC and both CEC (r = 0.49) and BS (r = 0.65) analytically confirm that SOC is the primary driver of the soil's functional capacity-its ability to retain nutrients and water. Ecologically, this low SOC translates directly to a compromised soil food web, limiting the energy and habitat necessary to sustain soil biodiversity and inhibiting essential ecosystem services such as nutrient cycling and the buffering capacity against climatic shocks like seasonal drought (Khadka et al. 2016; Audette et al. 2021; Telo 2023). Therefore, restoring SOC is not merely an input strategy but an essential step toward the ecological restoration of the district's farmlands.

The results reveal a state of nutrient inefficiency in Kubutambahan: High total stocks of P_2O_5 and total K_2O (r = 0.83, correlation) coexist with low overall fertility. This finding represents an ecological failure driven by the low SOC ceiling, which physically and chemically constrains the efficient retention and exchange of base cations. This inefficiency forces local farmers into continuous, costly reliance on external mineral inputs, a dependence cycle that often promotes monocultures and selects for high-input crop varieties over more resilient local landraces. This disparity may influence cropping patterns by encouraging reliance on input-dependent species, which could potentially affect agroecosystem diversity. Our data shows that the agricultural system currently favors nutrient storage over nutrient availability. Agronomically, this dictates that management must primarily focus on SOC amendments to restore the soil's buffering capacity before mineral fertilization can become ecologically effective.

The study's methodological novelty lies in linking the SOC deficit to HLU-based prioritized management strategies, which offer a robust blueprint for sustainable land management policy. The spatial variability confirmed that HLUs characterized by lower clay content and higher slopes (e.g., HLU 3, 6) exhibit lower CEC and higher vulnerability to erosion, making them ecological priority zones. For example, HLU 4, showing slightly acidic pH (6.53), highlights the need for localized lime application in contrast to other HLUs, where management must be geared toward organic matter incorporation. To address this spatial need, HLUs classified as low fertility must prioritize foundational ecological restoration through extensive use of compost/manure and legume-based intercropping (e.g., local legumes such as peanuts and mung beans), which naturally enhance SOC and N through biological fixation. Conversely, HLUs with medium fertility can transition to Integrated Nutrient Management (INM), balancing targeted mineral fertilization with organic inputs to maintain ecological stability.

An integrated synthesis of soil fertility indicators across Homogeneous Land Units (HLUs) is presented in Table 6. The table highlights a consistent pattern in which low Soil Organic Carbon (SOC) is associated with reduced Cation Exchange Capacity (CEC) and, in several cases, lower Base Saturation (BS), ultimately resulting in low to medium fertility status. Despite relatively high levels of P_2O_5 and K_2O across most HLUs, these nutrients are not effectively retained or utilized due to limited SOC, indicating a decoupling between nutrient availability and soil functional capacity.

Spatially, HLUs characterized by non-irrigated croplands and steeper slopes (e.g., HLU 6) exhibit the lowest SOC, CEC, and BS values, corresponding to low fertility status. In contrast, HLUs with more favorable conditions, such as forested or irrigated areas, show relatively higher CEC and BS, although SOC remains consistently low across all units. This integrated pattern confirms that SOC is the primary controlling factor of soil fertility in the study area and reinforces the need for HLU-based management strategies focused on organic matter restoration.

These findings demonstrate that improving soil fertility in Kubutambahan should prioritize strategies aimed at restoring soil organic matter rather than relying solely on additional mineral fertilization. Increasing organic inputs through compost, manure, crop residues, and legume-based systems may improve nutrient retention, enhance soil functional capacity, and ultimately increase the effectiveness of existing nutrient stocks across different HLUs.

Improving soil fertility in Kubutambahan is synonymous with enhancing its broader sustainability. Practical measures must include increasing organic matter inputs, adopting contour planting on sloping land, and integrating agroforestry systems to reduce erosion and enhance soil stability. For policymakers, the findings suggest the urgent need to support farmer access to organic inputs through subsidies and to strengthen agricultural extension programs that promote HLU-specific practices. To ensure the long-term effectiveness of these interventions and reinforce the study's scientific rigor, future research is strongly recommended to assess the economic feasibility of organic amendments for smallholders, conduct multi-seasonal sampling to account for climatic variability, and integrate digital monitoring tools and geostatistical methods (like Kriging) for quantitative validation of the spatial mapping (Trigunasih and Wiguna 2022; Abdehvand et al. 2024). This comprehensive approach ensures that land management supports both agricultural productivity and the long-term ecological health of the Buleleng landscape. Collectively, these findings demonstrate that nutrient inefficiency in Kubutambahan is not driven by elemental scarcity but by structural carbon limitations, reinforcing the need for ecological restoration rather than input intensification.

Overall, the results demonstrate that Soil Organic Carbon (SOC) functions as the central regulator of soil fertility in Kubutambahan Sub-district by influencing key nutrient dynamics, particularly Cation Exchange Capacity (CEC) and Base Saturation (BS). Despite the presence of relatively high P_2O_5 and K_2O levels, low SOC limits nutrient retention and availability, resulting in suboptimal fertility across HLUs. This interaction highlights a systemic imbalance between nutrient supply and utilization. Therefore, effective soil management should prioritize SOC restoration through organic matter inputs, which in turn enhances nutrient efficiency and supports site-specific (HLU-based) management strategies for sustainable agricultural productivity.

Table 6. Integrated summary of soil fertility indicators across Homogeneous Land Units (HLUs)

HLU	land use	Soil type	SOC (%)	CEC (me/100 g)	BS (%)	P_2O_5 (mg/100 g)	K_2O (mg/100 g)	Fertility Status
1	Scrub	Humus regosol	1.67	23.02	100.90	28.16	277.89	Low
2	Forest	Yellowish-brown latosol	1.71	26.59	69.42	23.45	236.28	Medium
3	Mixed plantation	Brownish regosol	1.59	13.26	92.31	118.63	439.85	Low
4	Mixed plantation	Grayish-brown regosol	1.68	24.40	180.53	236.69	483.76	Medium
5	Irrigated rice field	Brownish regosol	1.33	26.24	48.69	22.75	304.60	Medium
6	Non-irrigated cropland	Brownish regosol	1.18	10.36	19.61	78.25	466.37	Low
7	Mixed plantation	Brownish regosol	1.71	26.59	69.42	23.45	236.26	Medium

Note: SOC: Soil Organic Carbon, CEC: Cation Exchange Capacity, BS: Base Saturation. Classification of fertility status is based on the most limiting factor approach, following national guidelines

In conclusion, soil fertility in Kubutambahan Sub-district is predominantly low to medium, with 68.20% (8,380 ha) classified as low and 31.80% (3,908 ha) as medium. Soil Organic Carbon (SOC) was consistently identified as the primary limiting factor across all HLUs, with values ranging from 1.18% to 1.71%, indicating a system-wide deficit in soil organic matter. Despite generally high levels of P_2O_5 and K_2O, low SOC limits nutrient retention and exchange capacity, as reflected by its positive relationship with CEC (r = 0.49) and base saturation (r = 0.65). The most severe constraints occur in upland and non-irrigated areas, where low CEC and base saturation further reduce soil functional capacity. These findings highlight the need for HLU-based, site-specific management strategies that prioritize organic matter restoration through compost or manure application, mulching, legume-based intercropping, and erosion control on sloping land. This study is limited by single-season sampling and a small number of composite samples (n = 7), which constrain temporal and spatial inference. Future research should incorporate multi-seasonal data, higher sampling density, and geostatistical or remote sensing approaches to improve the robustness of soil fertility assessments and management.

ACKNOWLEDGEMENTS

The authors would like to thank the Institute for Research and Community Service (LPPM), Universitas Udayana, Indonesia, for the financial support provided so that this research activity can be carried out well.

REFERENCES

Abdehvand ZZ, Javaherian M, Kolahi M, Sabaeian M. 2025. Evaluation of the quality and phytochemical composition of sesame oil extracted using cellulase and pepsin enzymes. Appl Food Res 5 (2): 101046. https://doi.org/10.1016/j.afres.2025.101046.

Anim AO, Lutterodt HE, Ofori CW, Oduro-Boateng I, Bonsu JA, Ankar-Brewoo GM, Aduku LNE, Apprey C, Annan RA. 2025. The impact of agricultural practices on food composition: A systematic review. J Food Compos Anal 148 (Part 3): 108388. https://doi.org/10.1016/j.jfca.2025.108388.

Audette Y, Congreves KA, Schneider K, Zaro GC, Nunes ALP, Zhang H, Voroney RP. 2021. The effect of agroecosystem management on the distribution of C functional groups in soil organic matter: A review. Biol Fertil Soil 57: 881-894. https://doi.org/10.1007/s00374-021-01580-2.

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman M, Sukkel W, van Groenigen JW, Brussaard L. 2018. Soil quality - a critical review. Soil Biol Biochem 120: 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030.

Central Bureau of Statistics of Buleleng District. 2023. Kubutambahan Sub-district in Numbers. Central Bureau of Statistics of Buleleng District, Singaraja. [Indonesian]

Central Bureau of Statistics of Buleleng District. 2025. Kubutambahan Sub-district in Numbers. Central Bureau of Statistics of Buleleng District, Singaraja. [Indonesian]

de Vries W, Posch M, Simpson D, de Leeuw FAAM, van Grinsven HJM, Schulte-Uebbing LF, Sutton MA, Ros GH. 2024. Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: A review. Earth-Sci Rev 253: 104789. https://doi.org/10.1016/j.earscirev.2024.104789.

Dermawan R, Susila AD, Purwono P, Nugroho B. 2024. Evaluation of five soil nutrient extraction methods for practical assessment of phosphorus and potassium availability for tomato (*Solanum lycopersicum*) fertilization in Andisols-Garut, Indonesia. Acta Agrobot 77: 1-9. https://doi.org/10.5586/aa/187895.

Dossouhoui GIA, Yemadje PL, Berre D, Diogo RVC, Tittonell P. 2025. Understanding farm-level diversity to guide soil fertility management in West African cotton systems: Evidence from Benin. Agric Ecosyst Environ 392: 109749. https://doi.org/10.1016/j.agee.2025.109749.

Enang RK, Yerima BPK, Kome GK, Van Ranst E. 2018. Assessing the effectiveness of the Walkley-Black method for soil organic carbon determination in tephra soils of Cameroon. Commun Soil Sci Plant Anal 49 (19): 2379-2386. https://doi.org/10.1080/00103624.2018.1510948.

Guan K, Jin Z, Peng B, Tang J, De Lucia EH, West PC, Jiang C, Wang S, Kim T, Zhou W, Griffis T, Liu L, Yang WH, Qin Z, Yang Q, Margenot A, Stuchiner ER, Kumar V, Bernacchi C, Bernacchi C, Coppess J, Novick KA, Gerber J, Jahn M, Khanna M, Lee DK, Chen Z, Yang S-J. 2023. A scalable framework for quantifying field-level agricultural carbon outcomes. Earth-Sci Rev 243: 104462. https://doi.org/10.1016/j.earscirev.2023.104462.

Iticha B, Kamran M, Yan R, Siuta D, Al-Hashimi A, Takele C, Olana F, Kukfisz B, Iqbal S, Elshikh MS. 2022. The role of digital soil information in assisting precision soil management. Sustainability 14 (18): 11710. https://doi.org/10.3390/su141811710.

Karabayev K, Suleimenov B, Songulov Y, Akhmurzin U, Smanov A. 2025. Integrated application of granular and liquid bioorganic fertilizers improves corn productivity and soil fertility in light chestnut soils. Cell Biol Dev 9: 54-63. https://doi.org/10.13057/cellbioldev/v090105.

Kargas G, Londra P, Sotirakoglou K. 2022. The effect of soil texture on the conversion factor of 1:5 soil/water extract Electrical Conductivity ($EC_{1:5}$) to soil saturated paste extract Electrical Conductivity (EC_e). Water 14 (4): 642. https://doi.org/10.3390/w14040642.

Khadka D, Lamichhane S, Khan S, Joshi S, Pant BB. 2016. Assessment of soil fertility status of Agriculture Research Station, Belachapi, Dhanusha, Nepal. J Maize Res Dev 2 (1): 43-57. https://doi.org/10.3126/jmrd.v2i1.16214.

Kome G, Enang R, Tabi F, Yerima B. 2019. Influence of clay minerals on some soil fertility attributes: A review. Open J Soil Sci 9 (9): 155-188. https://doi.org/10.4236/ojss.2019.99010.

Kuunya R, Osman MMA, Ssemugenze B, Tamás A, Ragán P. 2026. Monitoring soil fertility trends linked to arable land-use change in Hungary, 2000-2020: A systematic review integrating field and remote sensing data. Agriculture 16 (8): 876. https://doi.org/10.3390/agriculture16080876.

Purnamasari L, Rostaman T, Widowati LR, Anggria L. 2021. Comparison of Appropriate Cation Exchange Capacity (CEC) Extraction Methods for Soils from Several Regions of Indonesia. IOP Conf Ser Earth Environ Sci 648 (1): 012209. https://doi.org/10.1088/1755-1315/648/1/012209.

Sofo A, Zanella A, Ponge JF. 2021. Soil quality and fertility in sustainable agriculture, with a contribution to the biological classification of agricultural soils. Soil Use Manag 38 (2): 1085-1112. https://doi.org/10.1111/sum.12702.

Soil Research Center. 1995. A Combination of Several Chemical Properties of Soil and Its Fertility Status. Soil Research Center, Ministry of Agriculture, Bogor. [Indonesian]

Sopialena, Rosfiansyah, Sila S. 2017. The benefit of top soil and fertilizer mixture to improve the ex-coal mining land. Nusantara Bioscience 9: 36-43. https://doi.org/10.13057/nusbiosci/n090107.

Sumarniasih MS, Antara M. 2021. Sustainable agricultural land management strategy in Buleleng District of Bali, Indonesia. J Dryland Agric 7 (5): 88-95. https://doi.org/10.5897/JODA2020.0064.

Suwardi. 2019. Utilization and Improvement of Marginal Soils for Agricultural Development in Indonesia. IOP Conf Ser Earth Environ Sci 383 (1): 012047. https://doi.org/10.1088/1755-1315/383/1/012047.

Telo JDGJ. 2023. The role of soils in sustainability, climate change, and ecosystem services: Challenges and opportunities. Ecologies 4 (3): 552-567. https://doi.org/10.3390/ecologies4030036.

Țopa D-C, Căpșună S, Calistru A-E, Ailincăi C. 2025. Sustainable practices for enhancing soil health and crop quality in modern agriculture: A review. Agriculture 15 (9): 998. https://doi.org/10.3390/agriculture15090998.

Trigunasih NM, Wiguna PPK. 2020. Land suitability for rice field and conservation planning in Ho watershed, Tabanan Regency, Bali Province, Indonesia. Geogr Tech 15 (1): 124-131. https://doi.org/10.21163/GT_2020.151.11.

Trigunasih NM, Wiguna PPK. 2022. Identification of soil fertility status of Subak rice fields based on soil chemical properties in Denpasar City, Bali, Indonesia. Afr J Food Agric Nutr Dev 22 (115): 21807-21824. https://doi.org/10.18697/ajfand.115.20880.

Zhang J, Qu X, Song X, Xiao Y, Wang A, Li D. 2023. Spatial variation in soil base saturation and exchangeable cations in tropical and subtropical China. Agronomy 13 (3): 781. https://doi.org/10.3390/agronomy13030781.