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Distribution of Soil Physical Characteristics Across Different Slope Gradients in Highland Areas (Tawangmangu, Indonesia) for Potato Crop Development

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Abstract

Tawangmangu District, Indonesia, is located in a highland area with a cool climate and is predominantly composed of Andisol soil types, offering great potential for the development of potato crops (Solanum tuberosum L.). This study aims to examine soil physical properties suitable for potato cultivation, analyze the distribution of these properties across different slope gradients, and identify appropriate soil management strategies for the Tawangmangu area. The research employed a descriptive-exploratory approach, utilizing land map units (LMUs) that were determined through the overlay of soil type maps, rainfall data, slope gradients, and land use. The overlay resulted in 5 LMUs and 25 sampling points. Observed soil physical parameters included texture, porosity, permeability, consistency, effective soil depth, coarse material, and drainage. The suitability of soil physical properties showed that LMU's 1, 4, and 5 were classified as S1 (highly suitable), while LMu's 2 and 3 were classified as S2-oa,rc, with drainage and texture as limiting factors. Slope gradient significantly affected moisture content ($p = 0.022$), bulk density ($p = 0.037$), particle density ($p = 0.048$), porosity ($p = 0.032$), effective soil depth ($p = 0.001$), and coarse material content ($p = 0.032$). Recommended land management efforts include the addition of organic matter, manual tillage for shallow soils, and the application of eco-drainage techniques to improve soil physical suitability for potato cultivation in Tawangmangu.

1. Introduction

Potato (Solanum tuberosum L.) is a high-value horticultural commodity with substantial potential as a raw material for the food industry and household consumption. Demand for potatoes continues to increase annually. According to data from the Central Statistics Agency (BPS), national potato consumption in 2021 reached 6.2 million tons, while domestic production was only around 1.4 million tons, resulting in a deficit of approximately 4.8 million tons, making Indonesia dependent on imports to meet domestic demand (BPS, 2022). In Central Java Province, particularly in Karanganyar Regency, BPS data indicate a significant increase in potato consumption from 2018 to 2022, with an average annual growth rate of 3.5%. This increase in consumption has not been matched by growth in local production, making the development of potato cultivation strategic priority.

Tawangmangu District in Karanganyar Regency is one of the highland areas agroclimatically suitable for potato cultivation. Located on the western slope of Mount Lawu at an altitude of 800–2,000 meters above sea level (asl) with daily temperatures ranging from 16–25°C (AccuWeather, 2025) and an annual rainfall of 2,000–2,500 mm, this area meets the optimal growth requirements for potatoes, which include temperatures of 17–20°C and elevations between 800–1,500 meters (Djuariah et al., 2017). However, potato productivity in Tawangmangu remains suboptimal. One of the main constraints is the complex topography, with slope gradients ranging from 1% to over 40%. The eastern part of Tawangmangu is characterized by steep slopes exceeding 40%, which makes land management challenging and increases the risk of soil degradation.

A primary cause of low potato productivity in this area is the suboptimal management of soil physical properties, particularly on sloped land that is vulnerable to degradation, including erosion and declining soil quality (Gobinath et al., 2022). Tawangmangu District is predominantly composed of Andisol soil types characterized by granular texture and high organic matter content. However, sloped lands in this highland area increase the risk of erosion and degradation of Andisols if not balanced with proper soil and water conservation measures (Bedadi et al., 2023). Furthermore, effective soil depth on steep slopes tends to be limited, which hinders root development and optimal tuber formation (Djaman et al., 2022). These conditions are exacerbated by high rainfall in highland areas, which, if left unmanaged, can lead to excessive surface runoff and further degrade soil physical quality (Chen et al., 2018). This study aims to evaluate soil physical properties suitable for potato crop development, analyze the distribution of these properties across different slope gradients, and provide appropriate management recommendations based on the results of this evaluation.

2. Methodology

2.1. Research Area Description

This research was conducted in Tawangmangu District, Karanganyar Regency, Central Java (Figure1). Astronomically, it is located between 07°37′30″ S and 07°42′00″ S, 111°04′00″ E and 111°12′00″ E. Tawangmangu has an average elevation of 1,200 meters above sea level. The area features a rugged topography with slopes ranging from 1% to over 40%. Its geographical position on the slopes of Mount Lawu results in the dominance of Andisol soils, which are rich in nutrients and highly suitable for the growth of horticultural crops (Anda et al., 2021). However, from 2020 to 2023, potato productivity in Tawangmangu has declined (BPS Karanganyar, 2024), which contradicts the region's favorable climate, soil, and topographical conditions. One likely factor is the deterioration of soil physical properties due to high erosion and surface runoff, which reduce organic matter content, infiltration capacity, and ultimately, agricultural productivity (Qiu et al., 2021; Henny & Arsyad, 2022; Banuwa, 2013; Sone et al., 2020).

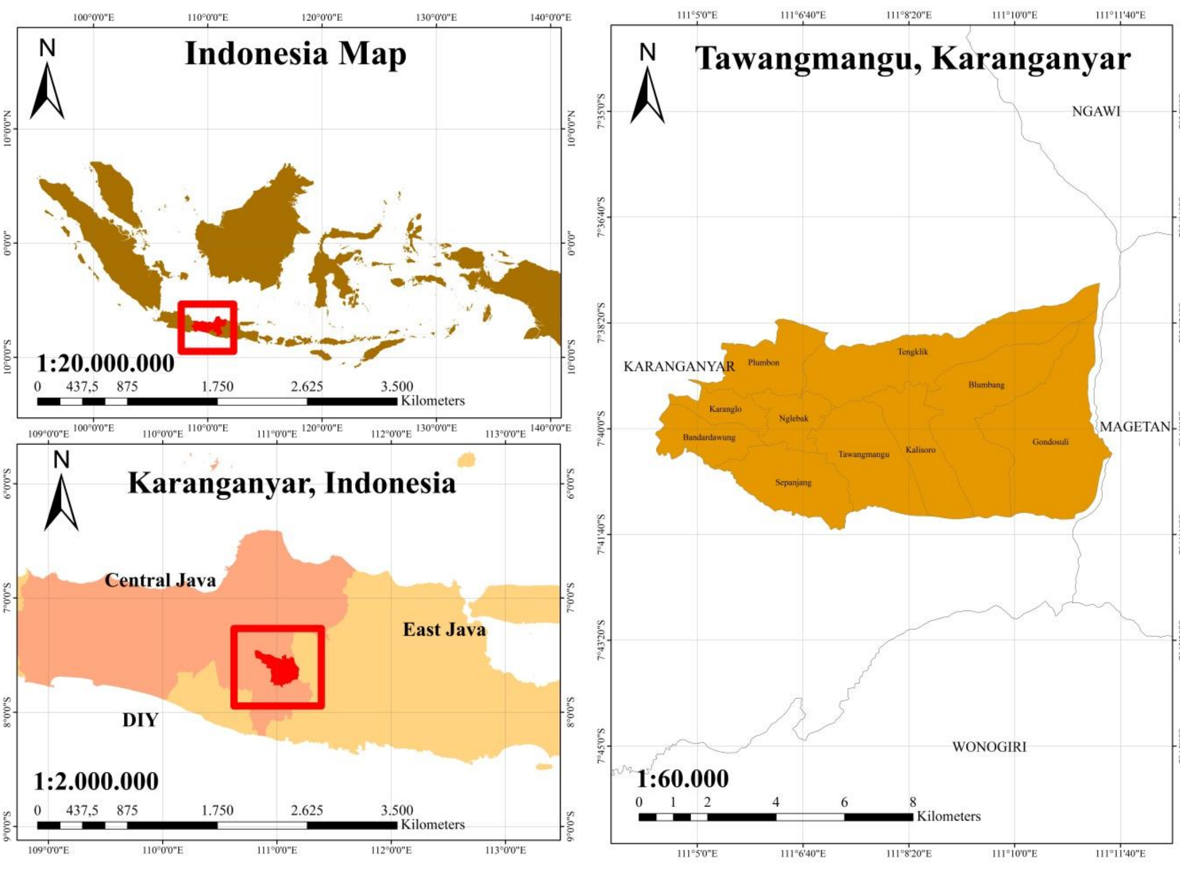

Figure 1. Map of Research Area

2.2. Observation and Sampling Point

This study employed a descriptive-exploratory method using a survey approach (Figure 2). Soil sampling used a random purposive sampling method based on the overlay of soil type, rainfall, slope gradient, and land use maps. The research focused on dryland areas intended for potato cultivation. A total of 25 soil sampling points were selected across 5 LMUs, with 5 points sampled per LMU. Field observations included effective soil depth, drainage, and the presence of coarse material. Laboratory-analyzed soil physical parameters included texture (pipette method), porosity (gravimetric and ring sample methods), permeability (falling head permeameter), soil consistency (atterberg limits), and moisture content (gravimetric method) (Kurnia et al., 2006).

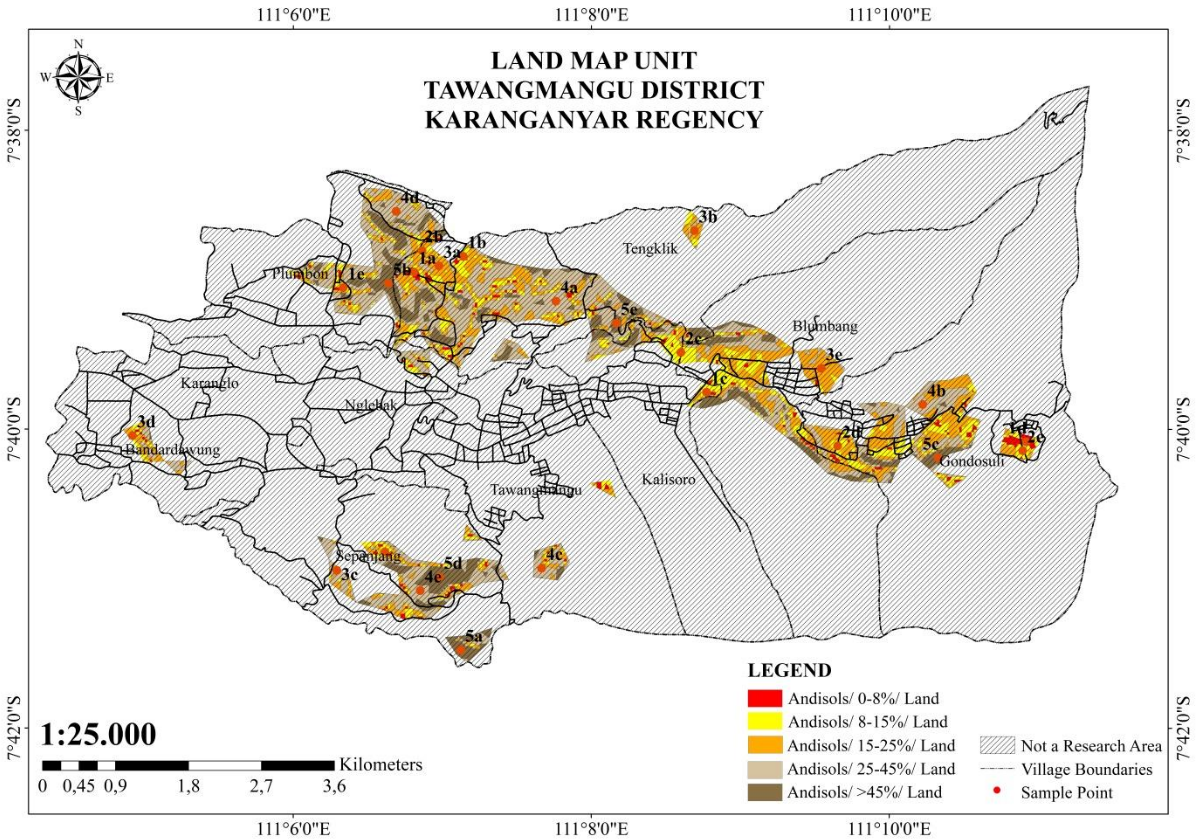

Figure 2. Map of Sample collection points in Tawangmangu District

2.3. Data Analysis

Data analysis involved describing both field and laboratory observation results. These results were then matched against potato crop growth requirements using the FAO land suitability evaluation method. Statistical analysis included ANOVA to test the effect of slope gradient on soil physical parameters, followed by DMRT for further differentiation and management recommendations.

3. Result and Discussion

3.1. Soil Physical Characteristics

The results indicate that soil physical characteristics in Tawangmangu District vary considerably across land map units (LMUs) (Table 1). Loam texture was found in LMU 1, sandy loam in LMUs 2 and 3, clay loam in LMU 4, and sandy clay loam in LMU 5. All five LMUs had sand content exceeding 40%. The dominance of sand fraction is attributed to volcanic parent materials containing coarse particles similar in size to fine sand (Arifin et al., 2022). This is supported by Solekhah et al. (2024), who noted that dryland areas generally have a sandy loam texture in residual zones and a silty clay texture in deposition zones. Such texture suggests relatively good drainage and aeration, meeting potato crop requirements for loose, well-drained soil. Hlatshwayo (2023) confirmed that a soil texture dominated by sand with low clay is favorable for potato cultivation. According to Silaban et al. (2016), the ideal soil textures for potatoes are moderately fine to medium. Based on the USDA classification, loam is categorized as medium, sandy loam as moderately coarse, sandy clay loam, and clay loam as moderately fine. Thus, loam, clay loam, and sandy clay loam are suitable for potato development.

Table 1. Land Suitability Class Criteria for Soil Physical Properties for Potato Crops (*Solanum tuberosum* L.)

Land Characteristics	Land Suitability Class			
	S1	S2	S3	N
Oxygen Availability (oa)				
- Drainage	Good, moderately slow	Moderately fast, moderate	Impeded	Severely impeded, rapid
Rooting Medium (rc)				
- Soil texture	Moderately fine, medium	Fine, Moderately coarse	Very fine	Coarse
- Effective soil depth (cm)	>75	50-75	30-50	<30
- Coarse material (%)	<15	15-35	35-55	>55

Table 2. Soil Physical Properties Analysis Results

LMU	Texture	Bulk Density (g/cm^3)	Particle Density (g/cm^3)	Porosity (%)	Permeability (cm/h)	Consistency
1	Loam	0.81	1.54	48.12	7.70	Low
2	Sandy Loam	0.62	1.30	52.60	12.62	Low
3	Sandy Loam	0.68	1.37	51.18	13.71	Low
4	Clay Loam	0.82	1.53	47,47	5.93	Moderate
5	Sandy Clay Loam	0.90	1.65	46,31	6.67	Moderate

Bulk density across the LMUs was relatively low (<1 g/cm^3), indicating low soil compaction, which supports high aeration and drainage (Stalham et al., 2015). This aligns with the Andisol properties, which typically have low bulk density due to their high allophane content (Hewitt et al., 2021). Henny and Arsyad (2022) found similar results, with Andisols in Kerinci having a bulk density of 0.73 g/cm^3.

Particle density was also low (<2 g/cm^3), attributable to high organic matter content in Andisols. Soils rich in organic matter tend to exhibit lower particle density (Lal, 2020). Porosity values ranged from 46.31% to 52.60%, falling within the fair to good category. The ideal porosity for horticultural crops, including potatoes, is approximately 50%, and can be improved through optimal tillage practices (Setiyo et al., 2023).

Permeability values varied among LMUs: LMU 1 (7.70 cm/h – moderately fast), LMU 2 (12.62 cm/h – fast), LMU 3 (13.71 cm/h – fast), LMU 4 (5.93 cm/h – moderate), and LMU 5 (6.67 cm/h – moderately fast). These differences stem from variations in texture, particularly in the amount of sand present. Higher sand percentages generally increase permeability because larger particles form larger pores (Hura & Gulo, 2024). The findings demonstrate that the soils can efficiently drain water, a critical condition for optimal root growth in potato crops (Liu & Chen, 2024). Slow permeability can lead to saturation and increased landslide risk (Kang & Yue, 2023).

Soil consistency in the five LMUs ranged from low to moderate plasticity. LMU 1 had a plasticity index of 10.30%, categorized as low; LMU 2 had a plasticity index of 8.09% (low); LMU 3 had 9.95% (low); LMU 4 had 11.86% (moderate); and LMU 5 had 11.71% (moderate) (Table 2). Soils with low to moderate plasticity are not overly plastic or sticky, making them easier to till (Silalahi et al., 2016).

3.2 Land Suitability Evaluation

Each plot of land has specific characteristics that significantly influence its quality. These characteristics may include the physical, biological, and chemical properties of the soil that affect land use for agricultural, settlement, and conservation purposes. According to Chiranjit Singha et al. (2019), land evaluation involves interpreting data on soils, landforms, climate, vegetation, and other aspects to identify and compare land uses that are promising and relevant to the evaluation's objectives. By understanding land characteristics and suitability evaluation components, land potential can be optimized while minimizing negative environmental impacts (Mesgaran et al., 2017). In this study, land characteristics evaluated for potato cultivation include oxygen availability (drainage) and rooting media (texture, effective soil depth, and coarse material content).

Table 3. Suitability of Soil Physical Properties

Land Characteristics	Land Map Unit (LMU)				
	1	2	3	4	5
Oxygen Availability (oa)					
- Drainage	Good (S1)	Moderately fast (S2)	Moderately fast (S2)	Good (S1)	Good (S1)
Rooting Medium (rc)					
- Soil texture	Loam (S1)	Sandy Loam (S2)	Sandy Loam (S2)	Clay Loam (S1)	Sandy Clay Loam (S1)
- Effective soil depth (cm)	>75 cm (S1)	>75 cm (S1)	>75 cm (S1)	>75 cm (S1)	>75 cm (S1)
- Coarse material (%)	<15% (S1)	<15% (S1)	<15% (S1)	<15% (S1)	<15% (S1)

Explanations: S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable

The suitability of soil physical properties in Tawangmangu District for potato cultivation is categorized as highly suitable (S1) and moderately suitable (S2) (Table 3). LMU's 1, 4, and 5 fall under the highly suitable (S1) class, while LMU's 2 and 3 are classified as S2-oa,rc due to drainage and texture limitations. The drainage in LMU's 2 and 3 is classified as moderately fast, allowing water to percolate through soil pores at a relatively fast rate, which reduces the soil's ability to retain water. Drainage limitation is considered moderately to highly manageable; improvement can be achieved by constructing appropriate drainage channels. Potatoes require soils with a loose structure, good drainage, and adequate aeration (Larkin et al., 2021). The soil texture in LMU's 2 and 3 is classified as sandy loam. Texture-related limitations, however, cannot be improved, as soil texture does not change significantly over a short period (Tarigan et al., 2016). This moderately suitable classification indicates that although the soils can be used for potato cultivation, significant management efforts are needed to address the limiting factors and enhance productivity (El Baroudy, 2016).

3.3 Distribution of Soil Physical Characteristics Across Slope Gradients

Soil physical properties are key factors in determining the suitability of land for potato cultivation (Figure 3). ANOVA and correlation analyses showed that slope gradient significantly influences soil physical characteristics in Tawangmangu District. The region's topographical variability across five slope classes has a significant impact on water distribution, erosion intensity, and the accumulation of soil particles and organic matter.

The slope gradient had a significant effect on several physical parameters: moisture content ($p = 0.022$), bulk density ($p = 0.037$), particle density ($p = 0.048$), porosity ($p = 0.032$), effective soil depth ($p = 0.001$), and coarse material ($p = 0.000$). This suggests that changes in slope have a significant impact on soil physical characteristics.

For instance, the moisture content was lowest at an 8–15% slope (9.26%) and highest at a 25–45% slope (14.51%) (Figure A). Although this contrasts with Simelane et al. (2024), who reported that steep slopes reduce infiltration opportunities, this result may be attributed to the presence of terracing and contour-aligned ridges at the sampling sites. Terraces can enhance water absorption by up to 75% in bench terraces and 68% in ridge terraces (Wibowo, 2010). Tando et al. (2019) also found that terracing increases water infiltration, reducing erosion.

The lowest bulk density (0.588 g/cm³) was found on slopes of 8–15%, while the highest value (0.9427 g/cm³) occurred on slopes of 25–45% (Figure B). Further analysis showed that steeper slopes tend to have higher bulk density. This finding is consistent with the results of Wubie and Assen (2020), who stated that steeply sloped land generally exhibits higher bulk density and lower total porosity. The increase in bulk density results from greater erosion and the loss of organic matter in the upper soil layer, which leads to soil compaction (Li et al., 2021). Additionally, on steep slopes, fine particles such as dust are easily transported by erosion to lower slopes.

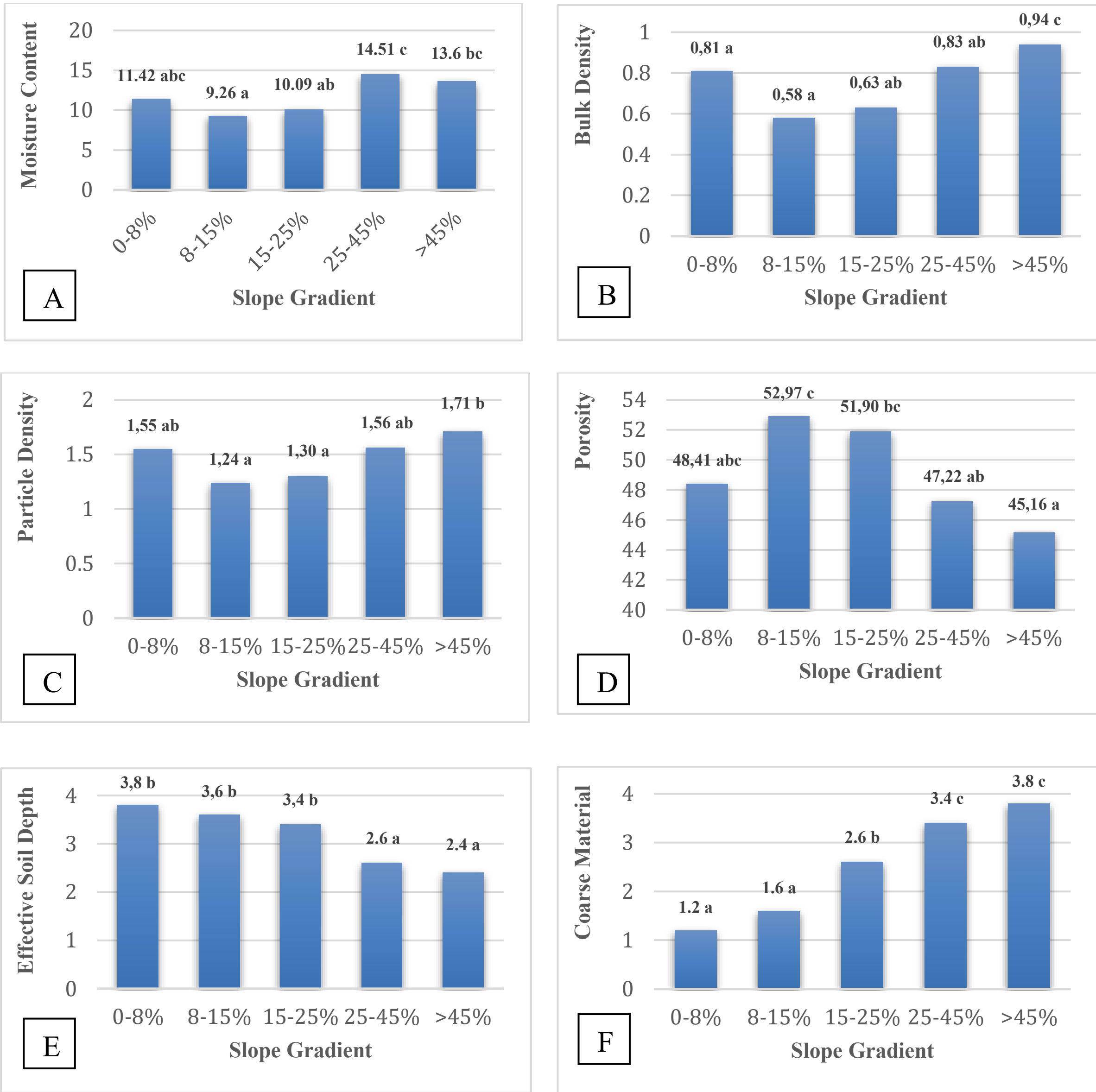

Figure 3. Distribution of Moisture Content (A), Bulk Density (B), Particle Density (C), Porosity (D), Effective Soil Depth (E), and Coarse Material (F).

According to Figure C, the lowest particle density (1.2444 g/cm³) occurred on 8–15% slopes, while the highest (1.7103 g/cm³) was on 25–45% slopes. Further analysis revealed that steeper slopes tend to have higher particle density. The lack of organic matter due to erosion on steep slopes causes fine particles to be easily carried away, leaving behind coarser particles (Wang et al., 2023). This is also supported by Isdin et al. (2024), who stated that dust particles are relatively fine and unable to form stable aggregates without bonding agents, making them highly susceptible to rain energy. The highest porosity (52.9722%) was observed on slopes of 8–15%, while the lowest (45.1677%) was found on slopes of 25–45% (Figure D). Further testing showed that soils on gentler slopes tend to have higher porosity. Land with smaller slope gradients experiences less erosion, resulting in higher organic matter content in the soil and increased soil pore space (Septiaji et al., 2024).

According to Figure E, the most excellent effective soil depth was found on slopes of 15–25%, while the shallowest was on slopes greater than 45%. Further analysis confirmed that the steeper the slope, the shallower the effective soil depth. This finding alligns with the results of Alfiyah et al. (2020), who reported that greater slope steepness typically yields shallower effective soil depth. Upper slope positions are more prone to erosion, causing the topsoil to be removed and deposited on lower slopes. As a result, effective soil depth tends to be greater at lower slopes compared to upper ones (Nugroho, 2016).

The lowest coarse material content (1.20%) was found on slopes of 0–8%, while the highest (3.80%) occurred on slopes greater than 45% (Figure F). Further analysis showed that the steeper the slope, the higher the coarse material content. Steep slopes tend to produce sediment with coarser particles (Defersha et al., 2011), as finer particles are more easily transported by surface runoff.

3.4 Soil Physical Property Management Strategy for Potato Crop Development

Soil physical property management in Tawangmangu District for potato development focuses on improving key physical parameters, including moisture content, bulk density, particle density, porosity, effective soil depth, coarse material content, and drainage. Potato plants require loose, porous, and sufficiently deep soils to ensure optimal root development and tuber formation. Proper soil physical management can reduce soil and water loss without significantly lowering potato yields (Záruba et al., 2023). Therefore, the recommended land management strategies include:

The addition of organic matter plays a crucial role in improving soil aggregation and enhancing the soil's ability to retain water and air, which are essential for plant growth. Incorporating organic materials, along with mulching, can increase the organic matter content and minimize plant stress (Kheyrodin et al., 2024). In addition, the application of organic mulch in potato cultivation helps maintain stable soil temperatures, preserve moisture, and suppress weed growth (Firdausy et al., 2024).

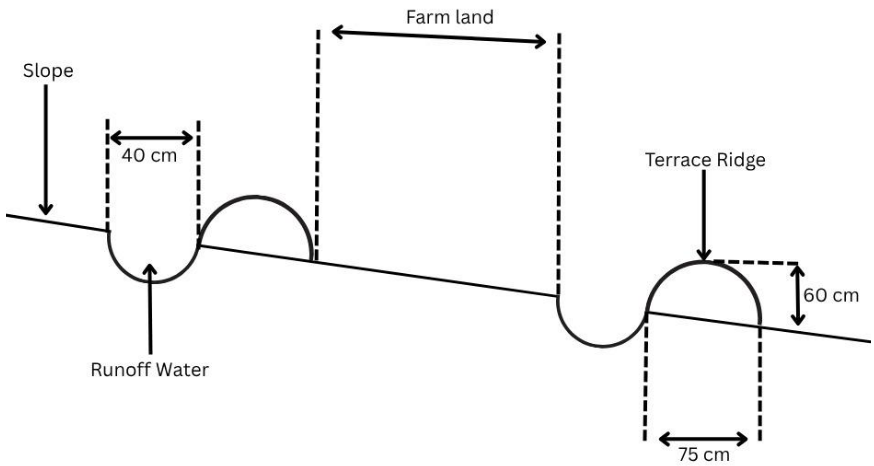

Figure 4. Ridge terrace

To address drainage issues on steeply sloped land, the application of soil conservation techniques is necessary, one of which is the eco-drainage system. Eco-drainage is a method of managing water runoff through natural infiltration into the soil or controlled flow into water bodies, ensuring that groundwater remains available during the dry season without causing waterlogging during the rainy season (Arsyad, 2012).

One form of eco-drainage suitable for sloped land is the ridge terrace (Figure 4), which consists of a series of ridges equipped with drainage channels located at the top of each ridge. According to Noywuli, N. (2023), a ridge terrace is composed of ridges, drainage channels, and cultivated strips. The drainage channels are constructed above the ridges to direct surface runoff from the cultivated area into designated water outlets. The function of the ridge terrace is to reduce the speed of surface runoff and enhance water infiltration into the soil.

The use of raised beds prevents potato roots from becoming waterlogged, thus reducing the risk of rot and supporting increased productivity. Therefore, eco-drainage through the implementation of ridge terraces and raised beds is an effective and sustainable strategy for potato cultivation on land with drainage problems. Meanwhile, soil texture limitations cannot be improved in the short term. Texture is an inherent soil property, making direct technical intervention unfeasible (Tarigan et al., 2016). As such, adopting the eco-drainage system represents a sustainable approach to soil and water conservation, supporting potato productivity in the highland areas of Tawangmangu.

4. Conclusion

This research demonstrates that the physical properties of soils in the Tawangmangu District vary across different land map units, with textures including loam, sandy loam, clay loam, and sandy clay loam. The soil texture is dominated by sand fractions exceeding 40%, with porosity ranging from poor to good and permeability categorized as moderate to rapid. The evaluation of land suitability indicates that LMU's 1, 4, and 5 are classified as S1 (highly suitable) for potato cultivation, while LMU's 2 and 3 fall under S2-oa,rc, limited by drainage and texture. Slope gradient significantly affects soil moisture content, bulk density, particle density, porosity, effective soil depth, and coarse material content. Therefore, improvements in soil physical properties, such as the addition of organic matter, the application of mulching, and the implementation of eco-drainage systems through ridge terraces and raised beds, are necessary to enhance the suitability of soil physical properties for potato cultivation in the highland areas of Tawangmangu.

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