

Research article

Land Suitability Evaluation for Citrus Cultivation using GIS and AHP for Different Land Units in Indonesia

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Abstract

The objective of this research is to evaluate the suitability of land for horticultural crops, particularly citrus cultivation, in an effort to increase productivity and support food security in Indonesia. The FAO land evaluation workflow through the Analytic Hierarchy Process (AHP) method was employed, together with the geographic information system (GIS), with several stages of activities such as preparation, survey and data analysis. In the initial stage, a land unit (LU) was formed to facilitate survey activities, data collection and data analysis. The data are analyzed for actual land suitability, followed by AHP analysis to determine relative priorities and potential land suitability. Our study shows that AHP technology is very effective in determining priority weights, as indicated by a consistency ratio (CR) value of <0.1. This condition implies a high and strong dependence on the environment. Environmental parameters that influence the evaluation and have a significant impact on citrus land suitability include rainfall (16%), drainage (15%), soil texture (12%) and erosion risk (4%). The results of the AHP analysis show that 18.57% of the study area is highly suitable (S1) for citrus plants; 65.28% is moderately suitable (S2); and 16.15% is slightly suitable (S3). The principal constraints of the soils are low nutrient content, poor rooting condition, and erosion risk. According to the study, management techniques such as the incorporation of organic matter and inorganic fertilizers, and the addition of mounding soil for plant systems, such as surface or subsurface drains, are required for long-term productivity.

Keywords: Land Unit; Analytic Hierarchy Process; Land Suitability; Citrus.

1. Introduction

Globally, citrus cultivation is spread across various regions, both tropical and subtropical, including Africa, Asia, South America, North America, and the Mediterranean. The three largest citrus-producing countries are Brazil (17 million tons/year), North America (9 million tons/year) and China (6 million tons/year) (Lima *et al.*, 2025); (Zhao *et al.*, 2023). Citrus crops are valued for their high economic value and for being rich in vitamin C and bioactive compounds that function to repair damaged cells. They are highly adapted to various climates, including Southeast Asia, which can contribute to the regional economy and biodiversity conservation (Li *et al.*, 2024).

Citrus is also one of the important horticultural crops and supports the economic growth of farmers and traders in Indonesia. It is also able to support soil preservation by accelerating rainwater infiltration and reducing runoff (Wu *et al.*, 2024). Citrus can grow in wetland systems, dry land, and even agroforestry systems (Liu *et al.*, 2024). Citrus today, in addition to being eaten directly, can be used for cosmetics, syrup drinks, other food flavors, fragrances, and medicines for various health treatments. There are several species of citrus are growing in Indonesia, including grapefruit, pomelo, tangerine, Medan citrus, lime, and sambal citrus. Tangerines are currently being developed to meet the demand for consumption of fruit in Indonesia, and comprise various types, including Malang and Semboro tangerines.

Citrus production in Indonesia currently ranges from 2.5 to 3.0 million tons/year, while national citrus demand is 4.0 to 4.5 million tons/year (Susila, 2013). The deficit in citrus supply in the country is a challenge to citrus farming, both in terms of intensification, extensification, climate change and technology, both pre- and post-harvest. Most islands in Indonesia can grow citrus, but Java Island has the largest area of cultivation, with 80% in East Java, spread across Malang, Jember, and Probolinggo (Ashari *et al.*, 2015). Citrus land in Jember totals 500 ha and is located in the Semboro and Rowokakung areas. Semboro tangerines are a local citrus variety with the Latin name *Citrus reticulata*. They are included in the Rutaceae family and have a characteristic round shape with slight flattening, a fruit diameter in the range of 5-7 cm (medium), and a weight of around 150-200 grams/fruit. They grow in the Tapal Kuda area of East Java. The productivity of Semboro citrus plants fell in 2023 compared to 2015. Production in 2015 was 144,995 quintals/ha/year, while in 2023 it was 111,624 quintals/ha/year (Bisnis, 2024). The harvest of Semboro tangerines is much higher compared to other regions. For example, Malang has a very high



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tangerine harvest of 290,126 quintals/ha/year, which is twice Indonesia's national average. These figures show that land conditions and supporting factors can affect citrus production; therefore, selecting a suitable area for citrus planting is important (Tantuoyir *et al.*, 2025).

GIS is an effective tool for integrating spatial data to comprehensively evaluate land suitability, especially for citrus cultivation. The technology enables location-based multi-criteria analyses that support a more accurate decision-making process (Tantuoyir *et al.*, 2025). The current application of GIS in agriculture has aimed to cool horticultural crops, plantations, and other crops (Leite *et al.*, 2024; Negussie *et al.*, 2024). By breaking down land use, GIS technology can provide clear boundaries and areas for each land suitability class (Basuki *et al.*, 2026).

Several previous studies have applied land suitability evaluation for horticultural crops, including citrus, using conventional approaches based on physical parameters and FAO criteria. For example, research conducted by Wang *et al.* (2022), Supriyadi *et al.* (2023) and Yang *et al.* (2024) relied solely on assessments based on soil classification and topography, without systematically integrating multi-criteria approaches. Optimization of agricultural productivity, such as citrus through land suitability assessment, rarely adopts advanced technology such as GIS, but instead the AHP method, and mostly in rice fields, with volcanic areas rarely assessed (Sathiyamurthi *et al.*, 2024; Sadiq *et al.*, 2025; Nuru *et al.*, 2025).

Moreover, most of these studies were conducted at the macro-scale or on homogeneous land units, which inadequately represent the spatial and ecological complexity of regions with diverse geomorphological conditions, such as volcanic tropical areas in Indonesia. Our study takes a scientifically novel approach by integrating the quantitative Analytical Hierarchy Process (AHP) with spatial GIS technologies within the complex geological context of Indonesia's volcanic regions, particularly the Argopura. This area stretches from the mountain's peak to the south coast of Java Island (the Indonesian Ocean). Current land use is mostly dependent on the rainy and dry seasons; at certain times, 45% is left as bushes, swamps, and empty land (Basuki *et al.*, 2024). Given the underutilized potential of high-value horticultural crops such as citrus, the approach makes a significant contribution to spatially informed decision-making and to enhancing land productivity in tropical mountainous regions. The innovation lies in the synergistic use of these two methods to more accurately assess land suitability for citrus cultivation, an approach rarely applied in areas with extreme topography and high soil variability. Therefore, this study aims to assess land suitability for citrus using GIS and AHP to strengthen sustainable agriculture.

2. Methods

2.1. Study Area

Indonesia is composed of islands and volcanoes formed by tectonic plate movements. There are approximately 500 volcanoes in the country, with some located in the horseshoe region of East Java, such as Mount Semeru, Mount Ijen, Mount Raung, and Mount Argopura. Mount Argopura has a peak at 3,088 meters above sea level, and its base borders the Indian Ocean. The volcano is currently inactive, so the central area, behind the foot of the mountain, is used for agriculture and plantations, including oranges, watermelons and durian, while plantation crops include sugarcane, tobacco, coffee, rubber and cocoa. Oranges are mostly planted in the volcanic soil area of the lower slopes of the mountain, located in three administrative districts: Tanggul, with an area of 9840.48 ha; Balung District, with an area of 4999.82 ha; and Bangsalsari District, with an area of 12750.24 ha. Geographically, the study area is located between 113°25'0"–113°35'30" E and 8°05'0"–8°08'0" S (Figure 1a). Land use in the three sub-districts consists of plantations covering 10,258.53 ha (44.48%), rice fields covering 2,189.93 ha (9.49%), and rice fields covering 10,617.19 ha (46.03%) (Figure 1b).

Mount Argopura significantly influences the environment and the resulting soil. Based on the great group level soil classification system, four subgroups are present, namely Andic Dystrudepts, which covers an area of 2,661.39 ha; Typic Epiaquepts, which covers an area of 8,523.55 ha; Typic Eutrudepts, which covers an area of 6,725.18 ha; and Typic Hapludands, which covers an area of 5,155.52 ha (Figure 1b). The depth characteristics of the large Andic Dystrudepts group (> 75 cm) consist of a fine soil texture fraction (silt and clay) of at least 30%. Typic Eutrudepts contains 0.2% or more organic carbon at a depth of 125 cm below the mineral soil surface (Ogg *et al.*, 2017). In the Typic Epiaquepts subgroup, the soil is very fine with a clay content of 66–83%, and the soil temperature is 50 cm below the isohyperthermic surface. The Typic Hapludands subgroup is soil formed from volcanic material, especially volcanic ash, which has a solum ranging from 30 to 40 cm from the surface (Jimoh *et al.*, 2020). Rainfall in the Mount Argopura region ranges from 1,500 to 4,000 mm/year. It occurs between September and February, with peak rainfall occurring in December. The dry season occurs between April and August, with the

optimal period in June, when evapotranspiration exceeds soil moisture. These rainfall conditions correlate with temperature, with air temperatures ranging from 20 to 27 degrees Celsius, increasing closer to the coast. The development of horticultural plants in the region continues to improve and is conducted in surrounding/satellite areas.

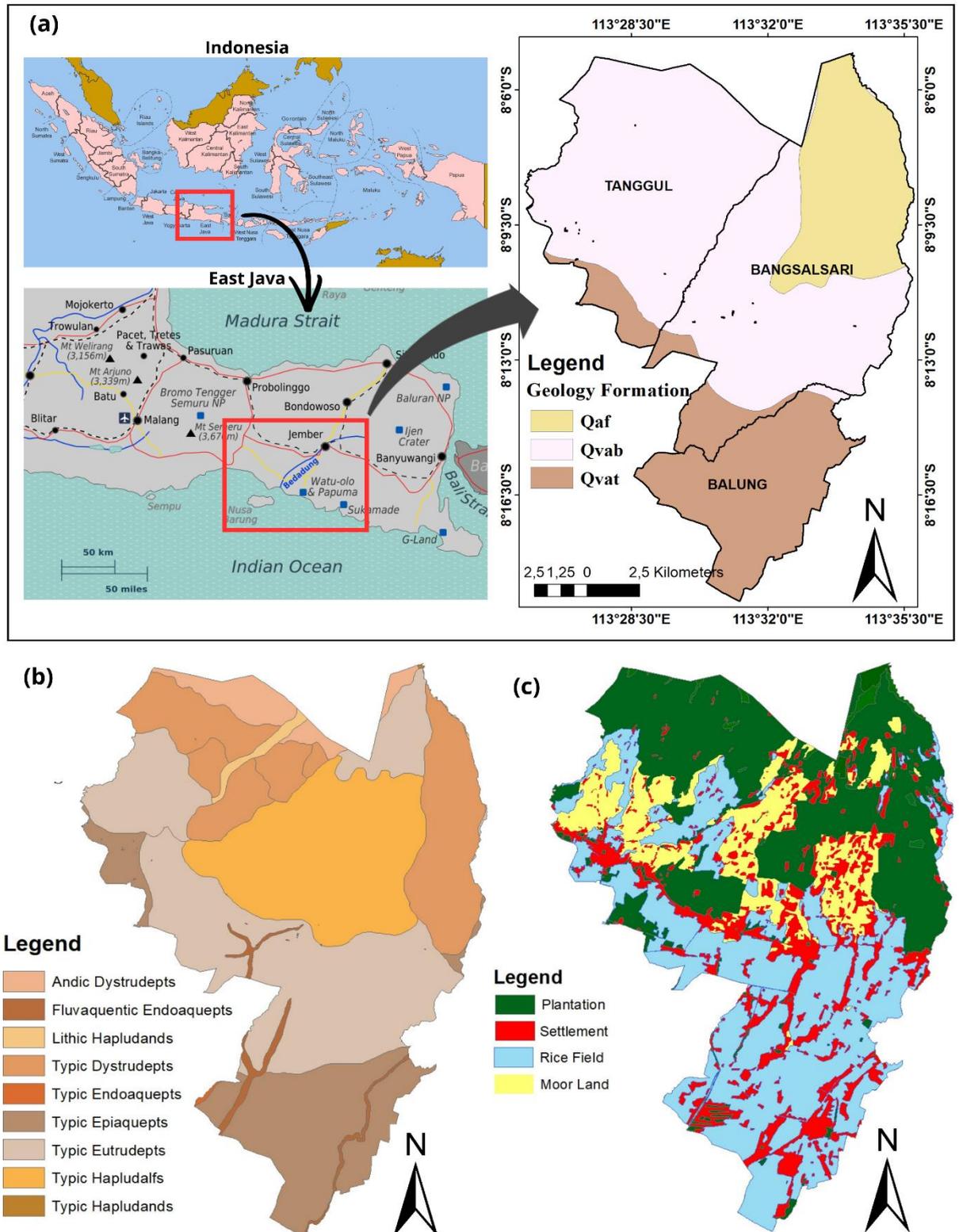


Figure 1. (a) Research Area, (b) Soil Type Map; (c) Land Use Map.

2.2. General Framework and Geodatabase Preparation

The study employed a descriptive exploratory method, with activities divided into three stages: preparation or pre-survey, survey, and analysis, to determine actual and potential land suitability using the AHP method (Figure 2). The first pre-survey activity was conducted to develop a working map, gather tools and materials, and collect quantitative data. The map was compiled

based on land differentiation factors, which served as the initial basis for identifying factors limiting citrus plant growth and development. It was compiled by overlapping three land characteristic maps: land use, slope, and soil type. This overlap produced land units that were a combination of the three factors. The land use characteristics used in the overlapping working map, designed to produce land units, were limited to plantations, dry rice fields and rice paddies; settlements and forests were not included. The overlap of these three land characteristics resulted in seven land units (Table 1).

Table 1. Description of Land units at the Research Location.

| Land Unit | Land Use | Slope (%) | Type Of Soil | Area (ha) | % |
|-----------|------------|-----------|-------------------|-----------|-------|
| 1 | Plantation | 8-15 | Typic Eutrudepts | 2.441,61 | 10.59 |
| 2 | Plantation | 15-30 | Typic Hapludands | 1.063,37 | 4.61 |
| 3 | Plantation | 8-15 | Andic Dystrudepts | 2.661,40 | 11.54 |
| 4 | Moor Land | 8-15 | Typic Epiaquepts | 2.189,93 | 9.49 |
| 5 | Plantation | 3-8 | Typic Hapludands | 4.092,15 | 17.74 |
| 6 | Rice Field | 3-8 | Typic Epiaquepts | 6.333,62 | 27.46 |
| 7 | Rice Field | 0-3 | Typic Eutrudepts | 4.283,57 | 18.57 |

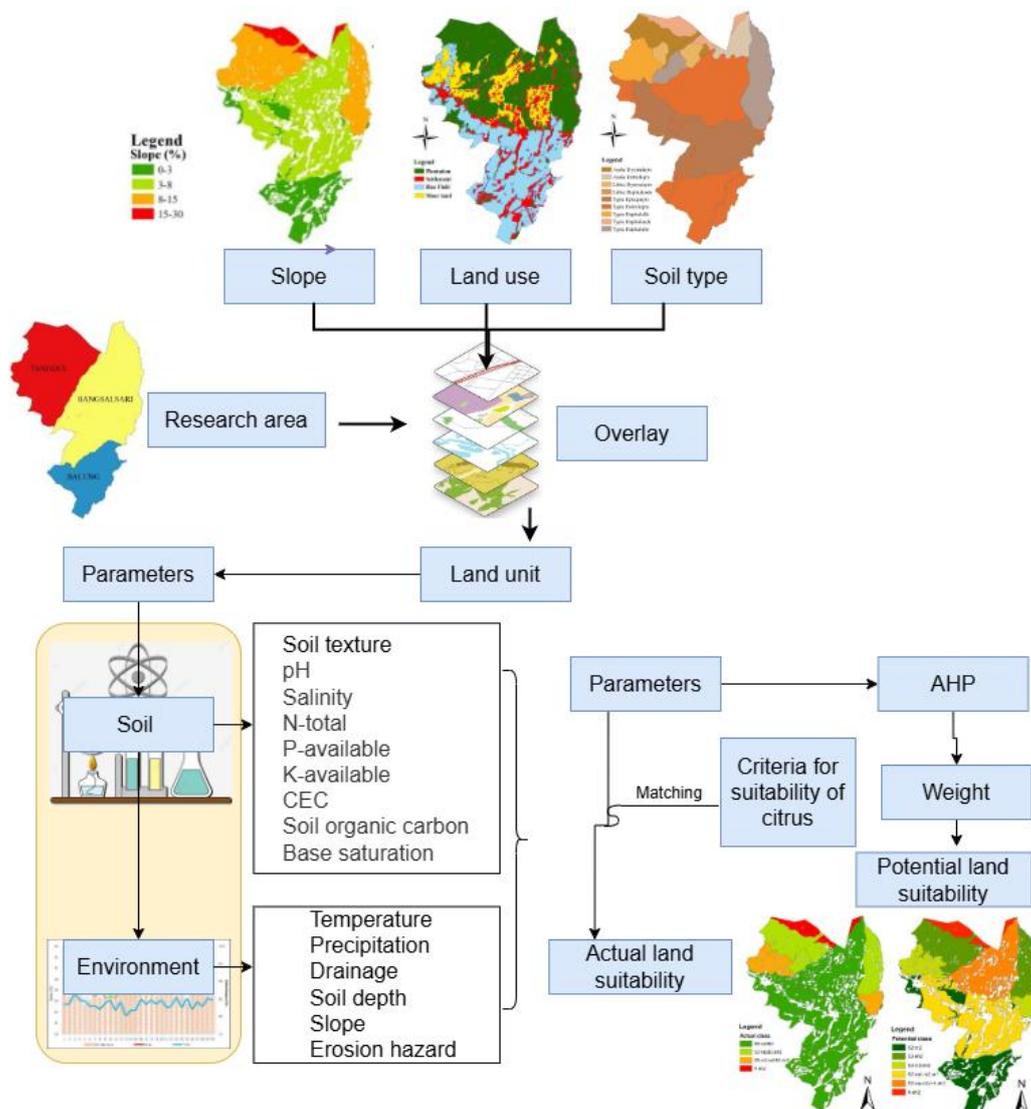


Figure 2. Land suitability chart analysis with the Analytical Hierarchy Process (AHP).

The second activity, a field survey, was conducted to collect soil samples and biophysical data for each of the prepared land units. The collection was conducted across all seven land units, with four replicate sampling points for each subunit. Each point was randomly selected to represent the subunit, with soil sampling ranging from 0 to 40 cm from the surface (Figure 3). Five replicate samples were then combined into one sample and labelled. The collected soil samples were used for chemical and physical soil analysis in the laboratory. The analysis began with the preparation of 2 mm air-dried soil samples. Observed soil characteristics included pH (H₂O), EC, available P,

total N, available K, CEC, organic C, base saturation, and soil texture. The soil chemical analysis method is shown in Table 2.

Biophysical observations conducted in each land unit included temperature, drainage, effective soil depth, rainfall, slope and erosion hazard. Temperature was measured using the Braak formula, which correlates temperature with altitude (Table 2). The average sea surface temperature is 26.3°C, and for every 100 meters of altitude above sea level, the temperature decreases by 0.6°C. Soil drainage was assessed in the field by observing the reduction and oxidation processes, indicated by visual rust or color on the soil surface (Figure 4). Soil depth was measured from the surface to the C horizon (100 cm) using a profile drill, then with a tape measure. Slope was measured using a DEM analysis in ArcGIS software. Erosion hazard was determined using USLE (Universal Soil Loss Equation) analysis (Table 2). This is a mathematical modelling method for predicting the long-term average annual soil erosion rate (A) based on factors such as rainfall (R), soil erodibility (K), slope length/slope (LS), and crop/conservation management (CP). The method is commonly used to evaluate erosion hazards in an area and plan appropriate soil conservation techniques.

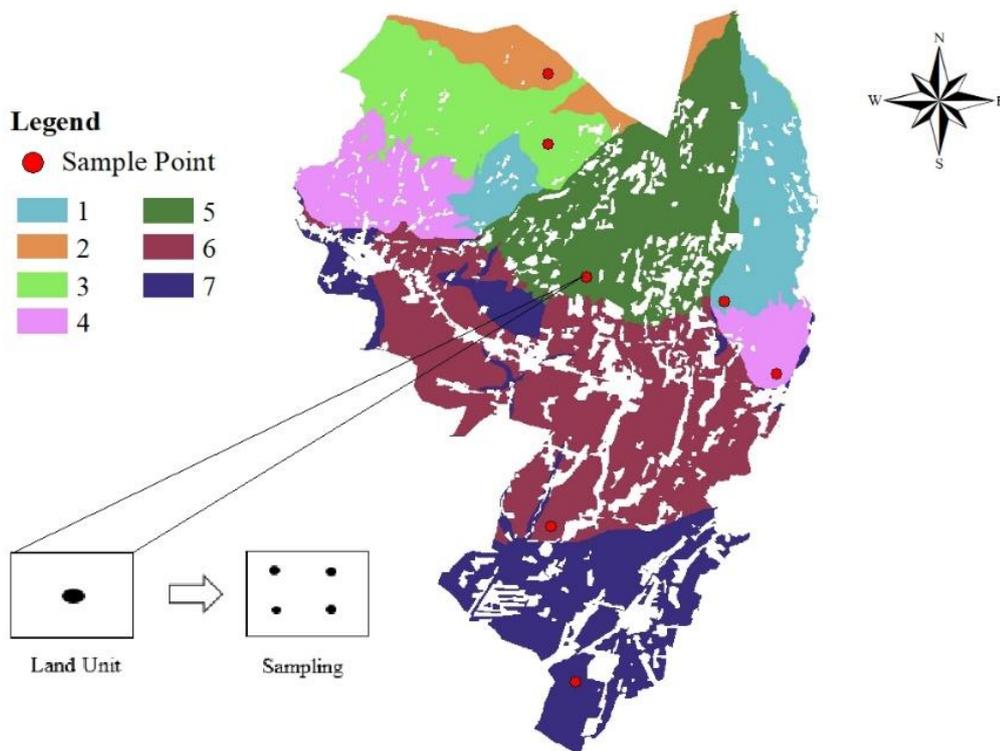


Figure 3. Land Map Units of the Research Locations and Soil Sampling .

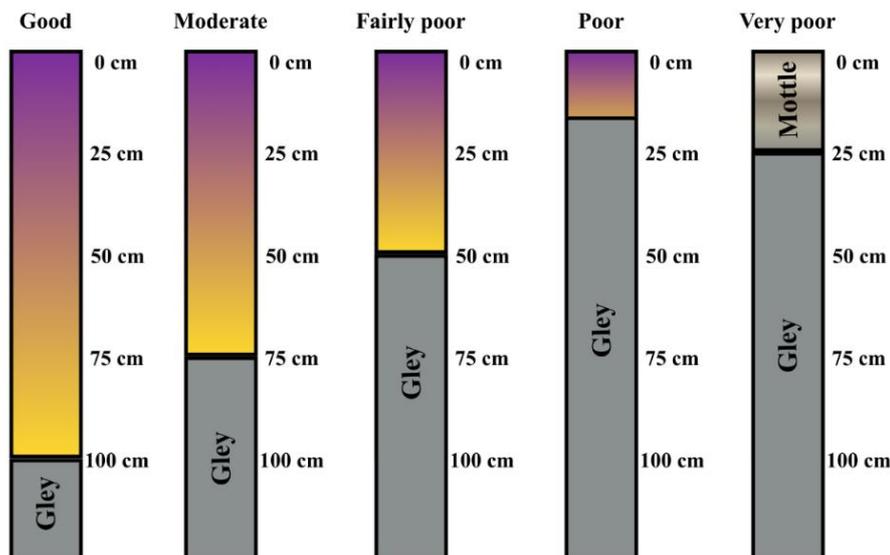


Figure 4. Identification of Soil Drainage.

Table 2. Environment and Soil Analysis Method for Land Suitability Parameters.

| No | Parameter | Method | Reference |
|--|----------------------|---|---|
| Environment | | | |
| 1 | Temperature | Braak formula (26.3oC-(0.01 X elevation X 0.6 oC) | (Chen <i>et al.</i> , 2021) |
| 2 | Drainage | Rust Identification (Redox Concentrations) | (Basuki <i>et al.</i> , 2025) |
| 3 | Effective soil depth | Boundary Layers Identified | (Taghizadeh-Mehrjardi <i>et al.</i> , 2020) |
| 4 | Precipitation | Manual Rain Gauge (Observation Type) | (Dornik <i>et al.</i> , 2024) |
| 5 | Slope | DEM | (Xing <i>et al.</i> , 2025) |
| 6 | Erosion hazard | USLE (Universal Soil Loss Equation) | (Basuki, <i>et al.</i> , 2023; Xue <i>et al.</i> , 2021) |
| Chemical and physical properties of the soil (laboratory) | | | |
| 1 | pH | Comparison of sample and distilled water 1:5 | (Zeraatpisheh <i>et al.</i> , 2020) |
| 2 | Salinity | Ec Meter | (Mustafa <i>et al.</i> , 2022) |
| 3 | P-available | Olsen | (Mustafa <i>et al.</i> , 2022) |
| 4 | N-Total | Kjedahl | (Mustafa <i>et al.</i> , 2022) |
| 5 | K-Available | NH4OAc extract pH 7.0 1M | (Basuki <i>et al.</i> , 2024) |
| 6 | CEC | NH4OAc extract pH 7.0 1M | (Basuki <i>et al.</i> , 2024) |
| 7 | C-Organic | Walkley-Black | (Mustafa <i>et al.</i> , 2022) |
| 8 | Base Saturation (BS) | NH4OAc extract pH 7.0 1M | (Mustafa <i>et al.</i> , 2022) |
| 9 | Soil Texture | Hydrometer | (Sedláčková <i>et al.</i> , 2024) |

2.4. Assessment of Suitability

Land evaluation assessment to determine the level of suitability of citrus crop commodities in Indonesia in line with environment and soil parameters was adopted from the FAO modifications developed by Sys, C. *et al.*, ([1991](#)) and Balittan Bogor, Indonesia (Basuki *et al.*, [2026](#)). The criteria for land suitability for citrus plants are the result of matching the soil and environmental characteristics associated with citrus productivity. The assessment utilized AHP, which matched the results of biophysical field analysis and laboratory analysis with citrus land suitability criteria as a basis for identifying factors that influence citrus productivity in the research area (Nuru *et al.*, [2025](#)).

AHP analysis is used to evaluate and prioritize factors by comparing their relative importance. Pairwise comparisons were made between the criteria, and a weight assigned to each based on their significance in determining land suitability (Negussie *et al.*, [2024](#)). This allowed for a systematic and objective way of ranking the criteria based on the land suitability for citrus cultivation. The AHP method is used to compare land characteristics pairwise based on the results of field and laboratory analysis, and provide weights to prioritize the influence of each factor on citrus crop productivity.

AHP is a decision-making technique that is used for evaluation and shows priority choices. It relies on pairwise comparisons to determine the relative importance of each criterion or option. Some experts argue that by giving weights first, followed by analysis using AHP, the technique is easier. AHP often has a weight range of 1-9 as a basis for ranking variables (Sadiq *et al.*, [2025](#)). The pairwise comparison matrix was used to generate priority weights, with the consistency ratio (CR) used to assess the reliability of the paired analysis. Equation (2) evaluates the CR, which ranges from 0 to 1, as described by Saaty and Malczewski (Negussie *et al.*, [2024](#)). The assessment is acceptable if it is less than 0.1. The consistency index (CI) was used as the basis for evaluation according to equation 1.

$$CI = \frac{\lambda \max - n}{n - 1} \tag{1}$$

where $\lambda \max$ is the highest eigenvalue of the pairwise model comparison, and n indicates the total number of classes (Abate *et al.*, [2024](#)). The CR value was obtained according to Equation (2).

$$CR = \frac{CI}{RI} \tag{2}$$

The index ratio (RI) value was determined by considering a random matrix of average CI values as described in the Saaty scale (Abate *et al.*, [2024](#)).

Table 3. Criteria for Land Suitability of Citrus.

| Land characteristics | Land Suitability Class | | | |
|---|--|--------------|--------------|-----------|
| | S1 | S2 | S3 | N |
| Temperature (tc) | | | | |
| Temperature (°C) | 19-33 | 33-36 | 36-39 | >39 |
| Water availability (wa) | | 16-19 | 13-16 | <13 |
| Rainfall (mm) | 1,200-3,000 | 1,000-1,200 | 800-1,000 | <800 |
| | | 3,000-3,500 | 3,000-4,000 | >4,000 |
| Oxygen availability (oa) | | | | |
| Drainage | Good, moderately good | Fairly poor | Poor | Very poor |
| Rooting condition (rc) | | | | |
| Soil Texture | Fairly coarse, medium, fairly fine, fine | - | Very fine | Coarse |
| Soil Depth (cm) | >100 | 75-100 | 50-75 | <50 |
| Nutrient retention (nr) | | | | |
| CEC (Cmol/kg) | >16 | <16 | - | - |
| Base Saturation (%) | >20 | <20 | - | - |
| C-Organic (%) | >0.8 | <0.8 | - | - |
| Nutrients available (na) | | | | |
| N-Total (%) | Moderate | Low | Very low | |
| P ₂ O ₅ (mg/100g) | High | Moderate | Very low-low | |
| K ₂ O (mg/100g) | Moderate | Low | Very low | |
| Toxicity (xc) | | | | |
| Salinity (dS/m) | <3 | 3-4 | 4-6 | >6 |
| Erosion hazard (eh) | | | | |
| Slope (%) | <8 | 8-16 | 16-30 | >30 |
| Erosion Hazard | Very low | Low-Moderate | High | Very high |

(Ritung *et al.*, 2011)

Land suitability assessment is based on multi-criteria decision analysis utilizing GIS technology with Quantum-GIS (Q-GIS) applications, particularly overlay models of weighted factors (Abuzaid & Abdelatif, 2022). The prerequisite criteria used to assess land suitability for citrus crops are shown in Table 3. Decision-making in assessing land suitability is divided into four classes for actual land suitability status, while for assessing potential land suitability status, AHP analysis is utilized. The results of the AHP analysis serve as the basis for management improvements and to determine the distribution of land suitability status, based on the S1 (highly suitable), S2 (moderately suitable), S3 (slightly suitable), and N (not suitable) classes.

3. Results and Discussion

3.1. Land Characteristics

1. Temperature

The temperature data used were obtained from the calculation results of the Braak formula ($26.30C - (0.01 \times \text{elevation} \times 0.6 \text{ oC})$) (Chen *et al.*, 2021). Temperature is a triggering factor in the physical process in the formation of clay from parent material minerals in the soil (Zhong *et al.*, 2019). The study's temperature distribution map, especially along the slopes of Mount Argopuro, is shown in Figure 5a. Based on the figure, land unit 1 has the lowest temperature value, 24.61°C, with an area of 2,441.61 ha, or 10.59% of the total area. The highest temperature was found in land unit 3, with a value of 26.26°C, and an area of 2,661.40 ha, or 11.54% of the total area. Variations in temperature can occur due to different topographic positions (How Jin Aik *et al.*, 2021). On different land maps, they can be influenced by differences in altitude, which is an important parameter used to evaluate the adequacy of land as a growth factor for the cultivation of plants. Temperature can also affect plant productivity (Dornik *et al.*, 2024). Safe temperatures for citrus plants are generally at 19 - 33°C; if the temperature is higher than 33°C, the plant will experience damage to the coloring of the fruit due to a decrease in nutrient content and consequently affect the taste of the fruit, making it less fresh.

2. Precipitation

Rainfall (mm) is the amount of rainwater expressed in mm. It is used as a physiological factor in plants, and as an indicator to determine their water needs in the event of drought (Ng *et al.*, 2024). Moreover, rainfall is an indicator of humidity, which is an important factor in the plant growth

process and affects plant productivity (Getachew *et al.*, 2021). The distribution of average rainfall over the last 10 years is shown in Figure 5b. Based on the figure, the highest rainfall is in Tanggul sub-district, with 2665.86 mm/year, affecting 35.67% of the total area (9840.48 ha), while the lowest is in Balung sub-district, with 2154.88 mm/year over an area of 4999.82 ha, 18.12% of the total area. Annual rainfall has a strong influence on crop management and is therefore an important factor, as rainwater functions as a solvent and transporter that can influence soil properties, soil minerals, and soil profile depth differentiation. Rainfall of between 1,000 -3,000 mm/year is the optimal level for citrus plants (Li *et al.*, 2024).

3. Drainage

The cultivation of plants can be optimized by good drainage, which maintains soil moisture and aeration (Sadiq *et al.*, 2025). The distribution of soil drainage in the research area is divided into two drainage classes: good and somewhat obstructed. Land units 1, 4 and 7, with an area of 8,915.11 ha, or 38.65% of the total area, have good drainage, while land units 2, 3, 5 and 6, with an area of 14,150.54 ha, or 61.35% of the total, are classified as having somewhat obstructed drainage. Soil with good drainage is characterized by a homogeneous soil color and no rust (manganese) or gley-related color at depths > 120 cm in the lower layer. This is in line with Aburas *et al.*, (2017), who state that a homogeneous soil color without spots (rust) can be a characteristic of good drainage, especially in layers up to > 100 cm. In citrus plants, soil drainage conditions greatly affect whether they grow well. Citrus plants can grow optimally with good drainage conditions at a soil depth of up to 120 cm.

4. Slope

Slope is a measure of an area in degrees or percentage. In addition to determining the level of land suitability, slope also affects the level of erosion and landslides (Dutta *et al.*, 2024). Determination of plant types on each slope also needs to be made, as plants are protectors of the soil surface (Miao *et al.*, 2022).

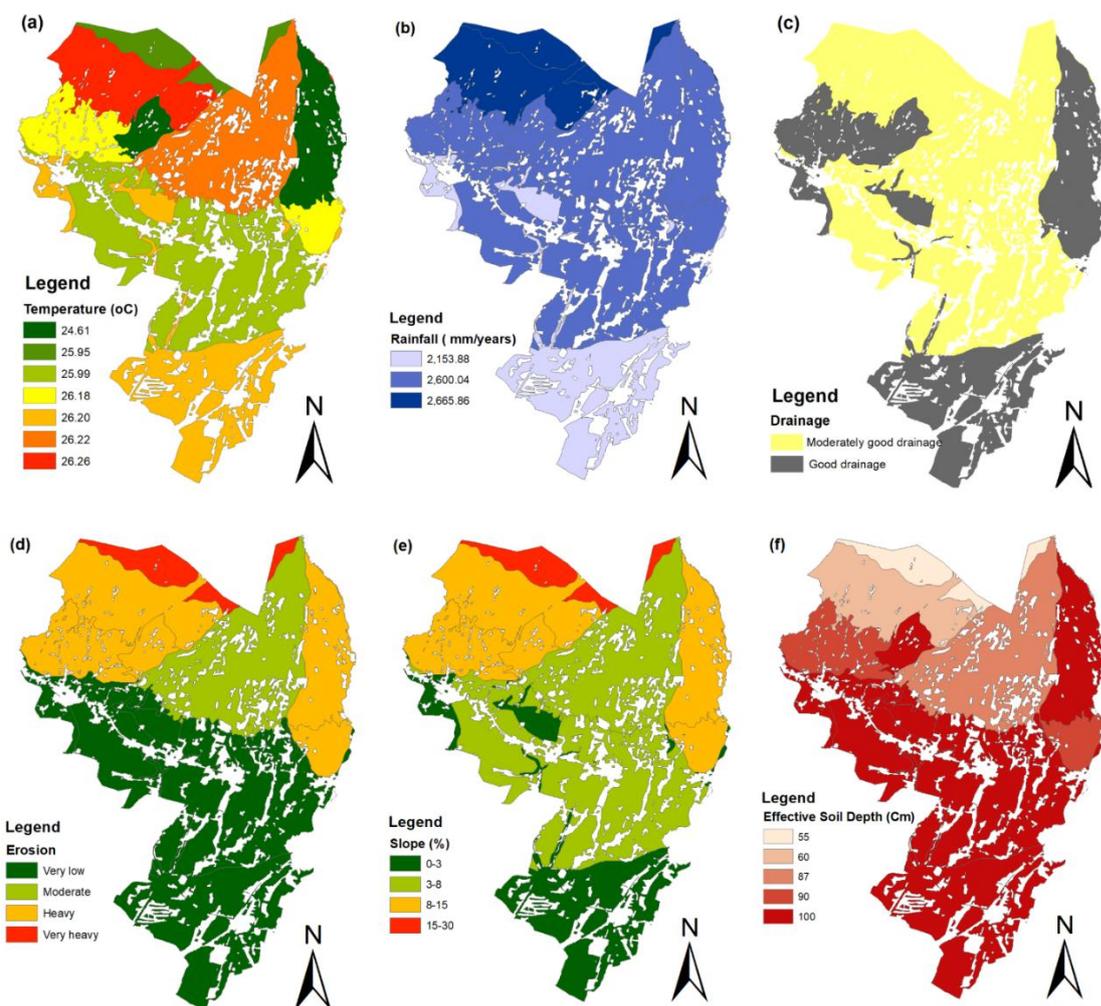


Figure 5. Land Characteristics: a) Temperature, b) Rainfall, c) Drainage, d) Erosion, e) Slope, f) Effective Soil Depth.

Therefore, the selection of plant types in line with the slope gradient is very important to maintain slope stability. The distribution of slopes in the research area is shown in Figure 5e. Based on the figure, there are four slope gradient classes: a flat class covering an area of 4,283.57 ha; a gentle area of 10,425.77 ha; a slightly sloping area of 7,292.94 ha; and a sloping area of 1,063.36 ha. Very steep land will affect the level of soil erosion (Yeneneh *et al.*, 2024). Steep land is not suitable for planting agricultural commodities because of the high erosion value, which will subsequently affect the nutrient content of the soil. An increase in surface runoff flow velocity can be caused by the steepness of the slope; this will also increase the surface flow transport energy (Sugianto *et al.*, 2022).

5. Erosion Hazard

Erosion refers to the loss of the top soil layer due to the movement of water and wind. Steep slope conditions increase the volume of surface runoff, which causes erosion (Basuki *et al.*, 2024). The distribution of erosion hazards are shown in Figure 5d. The figure indicates that at the research location there are four classes of erosion hazard: very severe, covering an area of 1,063.36 ha; severe, covering an area of 7,292.94 ha; moderate, covering an area of 4,092.15 ha; and very low, covering an area of 10,617.19 ha. The erosion hazard class that dominates the research area is that of very low, with 46.03% of the total area.

6. Effective Soil Depth

The depth of the soil layer that can be used for plant root growth is referred to as effective depth. If this is limited by barriers such as hard rock, solid rock, or other layers, it will inhibit root growth (Hofmann *et al.*, 2024). The distribution of effective depth in the research area is shown in Figure 5f, which indicates that the effective depth in this area is quite varied, with depths of 55-100 cm. Land units 1, 6 and 7 have the same depth, 100 cm, which is included in the deep category. Land units 2 and 3 are included in the medium category, with depths of 55 cm and 60 cm. Effective depth can be measured in the field by observing the fine roots of plants compared to the coarse ones, and other roots growing within them. Effective depth is influenced by the presence or absence of parent material, gravel or boulders, which cannot be penetrated by roots (Cyio, 2008). 82.93% of the research area has an effective depth in the deep category, while 17.07% has a medium effective depth. Soil depth is divided into deep (>75 cm), medium (50-75 cm), shallow (20-50 cm), and very shallow (<20 cm) classes (Subardja *et al.*, 2016). Effective depth can be influenced by root development; if the soil depth is shallow, this will inhibit such development. Depths of up to 120 cm are suitable for citrus plants.

3.2. Physical and Chemical Soil Characteristics

1. Texture

Soil texture in a soil mass is defined as the ratio of the content of sand, silt, and clay fractions. The percentage of particles determines the soil texture, with the texture class determined according to the USDA (Sadiq *et al.*, 2025). The distribution of soil texture is shown in Figure 6.a. It is divided into four texture classes sandy clay, covering 39% of the total area (8,995.02 ha); sandy loam, with an area of 6,752.18 ha (29.16%); silty clay loam covering an area of 2,189.93 ha (9.49%); and silty clay with an area of 5,155.52 ha. (22.35%). Each land unit has a different texture resulting from differences in the soil formation process and the soil management practiced. Soil texture affects the availability of nutrients and water due to its ability to bind and exchange cations in the soil. Soil with a clay texture stores nutrients and has sufficient water to allow air circulation (Nuru *et al.*, 2025). Because of the many micropores in the sand, air and water movement is very fast. A good texture for citrus growth is soil that is fine in texture and dominated by some dusty and clayey textures.

2. Cation Exchange Capacity

Cation exchange capacity (CEC) is a process that occurs in the soil by which cations are exchanged for available cations and vice versa. Cation exchange capacity is influenced by the presence of clay, nutrients and organic matter. A higher CEC value indicates better soil fertility status and vice versa (Mustofa *et al.*, 2024). Its role is very complex, as the formation and maintenance of soil fertility are supported by soil pH, soil C-organic factors, and the availability of organic material. The cation exchange capacity of each land unit in the study area is shown in Figure 6b. As shown in the distribution map in the figure, the CEC value in the research area has only two classes: low and medium. Land units 1, 2, 3, 4 and 5, with a total area of 12,448.46 ha (53.97%), are included in the low grade, while land units 6 and 7, with a total area of 10,617.19 ha (46.03%), are included in the medium grade. The lowest CEC value is in land unit 2, at 10.37 cmol/kg, with an area of 1,063.37 ha, and the highest CEC value was in land unit 7, namely 19.08 cmol/kg

corresponding to an area of 4,283.57 ha. The cation exchange capacity in the study area is low as the soil colloids contain clay and a low level of organic matter. Furthermore, CEC is influenced by soil moisture, with the ideal soil moisture for cation exchange being > 60%.

3. Base Saturation

Base saturation refers to base cations such as magnesium, calcium, sodium and potassium in the soil colloids. It can increase as a result of increased soil organic matter content (Jimoh *et al.*, 2020). The base saturation distribution map is shown in Figure 6c, which indicates that there are various base saturation values ranging from low to medium and high categories. Land unit 7, with an area of 4,283.57 ha, or 18.57% of the total area, is included in the lowest category, with a value of 36.83%. Land unit 2, with an area of 1,063.37 ha, or 4.61% of the total area, is in the highest category, with a base saturation value reaching 67.21%. The medium category includes land units 1, 3, 4, 5 and 6, with vulnerable values of 42.23–56.71%. The base saturation value can be influenced by rainfall and soil pH. High rainfall in Indonesia results in high levels of nutrient leaching, so alkalis in the soil are leached out. Low base saturation causes the bases in the soil to become acidic. Apart from rainfall, a high pH in soil usually corresponds to high base saturation, and vice versa.

4. Soil pH

Soil pH depends the presence of compounds in the soil, which can be acidic, neutral and alkaline. The level of soil acidity is used to define the suitability of land for certain crops (Tantuoyir *et al.*, 2025). Soil pH affects plant growth. If high H⁺ ion values are found in the soil, soil pH decreases, causing plants to be contaminated with microelements and increasing the solubility of iron and aluminum ions. Based on the pH distribution map shown in Figure 6d, the soil pH distribution ranges between 5.64 and 7.14, corresponding to the neutral and slightly acidic categories. Land unit 4, with an area of 2,189.93 ha, and land unit 5, covering 4,092.15 ha, are classified as having slightly acidic pH, while land units 1, 2, 3, 6 and 7 are classified as having neutral pH. Citrus plants can grow in various types of soil. The ideal pH is between 5 and 6; if the pH is less than 5, then the plant roots do not develop well, and the plant cannot absorb nutrients. On the other hand, soil with a pH of more than 6 usually has many bound macroelements, which is disturbing and abnormal for plant growth due to the lack of nutrients (Basuki *et al.*, 2022; Basuki & Sari, 2020).

5. Soil Organic Carbon

Soil organic carbon (C-Organic) in the soil increases soil fertility and the process of nutrient availability, which ultimately boosts the productivity of cultivated plants (Mustofa *et al.*, 2024). The C-Organic content supports the availability of organic materials derived from the decomposition of living things. Its distribution on the slopes of Mount Argopuro is shown in Figure 6e, ranging from 1.18 to 1.94%, with a low value; this indicates that the C-Organic content across all land units is very similar. Soil fertility is indicated by the presence of soil organic carbon in the soil, which is food for organisms; the number and diversity of types of organisms working in the soil also increase. Low soil organic carbon content in soil can be caused by intensive land cultivation (Mustofa *et al.*, 2024). Low C-organic content in soil can reduce productivity and plant growth. One way to overcome this is by adding fertilizer or organic material.

6. N-Total

Nitrogen is an important element for plants. Its level in soil varies greatly due to factors such as land cover, climate, landform, and soil chemical-physical properties. In turn, many factors influence the nitrogen content of plants, such as climate, vegetation, topography, and chemical-physical properties of the soil (Zhao *et al.*, 2023). The distribution of N-total in the study area can be seen in Figure 6f. The highest value of 0.18% is in land unit 2, with an area of 1,063.37 ha, and the lowest of 0.11% in land unit 1, with an area of 2,441.61 ha; however, both values are still in the low category. Another factor that influences the N-total value is organic matter. A low value in soil is a result of several factors, such as leaching with water, evaporation, and absorption by plants (Zhu *et al.*, 2024). The efficiency of N element absorption relates to the denitrification of N₂ gas.

7. P₂O₅

Phosphorus is a nutrient needed by plants. The P element content is usually lower than that of other nutrients, such as nitrogen and potassium. Plants absorb P in the form of primary orthophosphate (H₂PO₄) and secondary orthophosphate ions (HPO₄) (Oliveira *et al.*, 2021). The distribution of P₂O₅ in the study area can be seen in Figure 6g. Its value in all land units on the slopes of Mount Argopuro is in the low category (Figure 6g). The highest P₂O₅ value is 10.3 mg/100 g in land unit 2, with an area of 1,063.37 ha (4.61%), and the lowest available p-value is 7.83 mg/100

g in land unit 6, with an area of 6,333.62 or 27.46% of the total area. Several factors, such as soil texture, organic matter and soil pH influence the level of P values (Xu *et al.*, 2016). Low available P content is due to low phosphorus content in organic and mineral matter; poor pH also affects P elements. Low P levels in soil indicate leaching of phosphorus. Generally, phosphorus dissolves more easily in soil that has an acidic pH.

8. K₂O

The element potassium is one of the essential elements needed by plants to grow and develop. It functions, for example, by helping the development of roots in the soil and increasing plant resistance (Oliveira *et al.*, 2021). Based on Figure 6h, which shows the K₂O distribution map of each land unit in the research area, the K₂O value is in the very low category. The highest K value, 9.68 mg/100 g, is in land unit 4, with an area of 2,189.93 ha or 9.49% of the total area, while the lowest value, 9.25 mg/100 g, is in land unit 6, with an area of 6,333.62 ha or 27.46% of the total. The K₂O value in each land unit is very low. Low K content occurs because of the low efficiency of the leaching of potassium fertilizer, which is caused by the increased binding or leaching capacity of potassium (Zhu *et al.*, 2024).

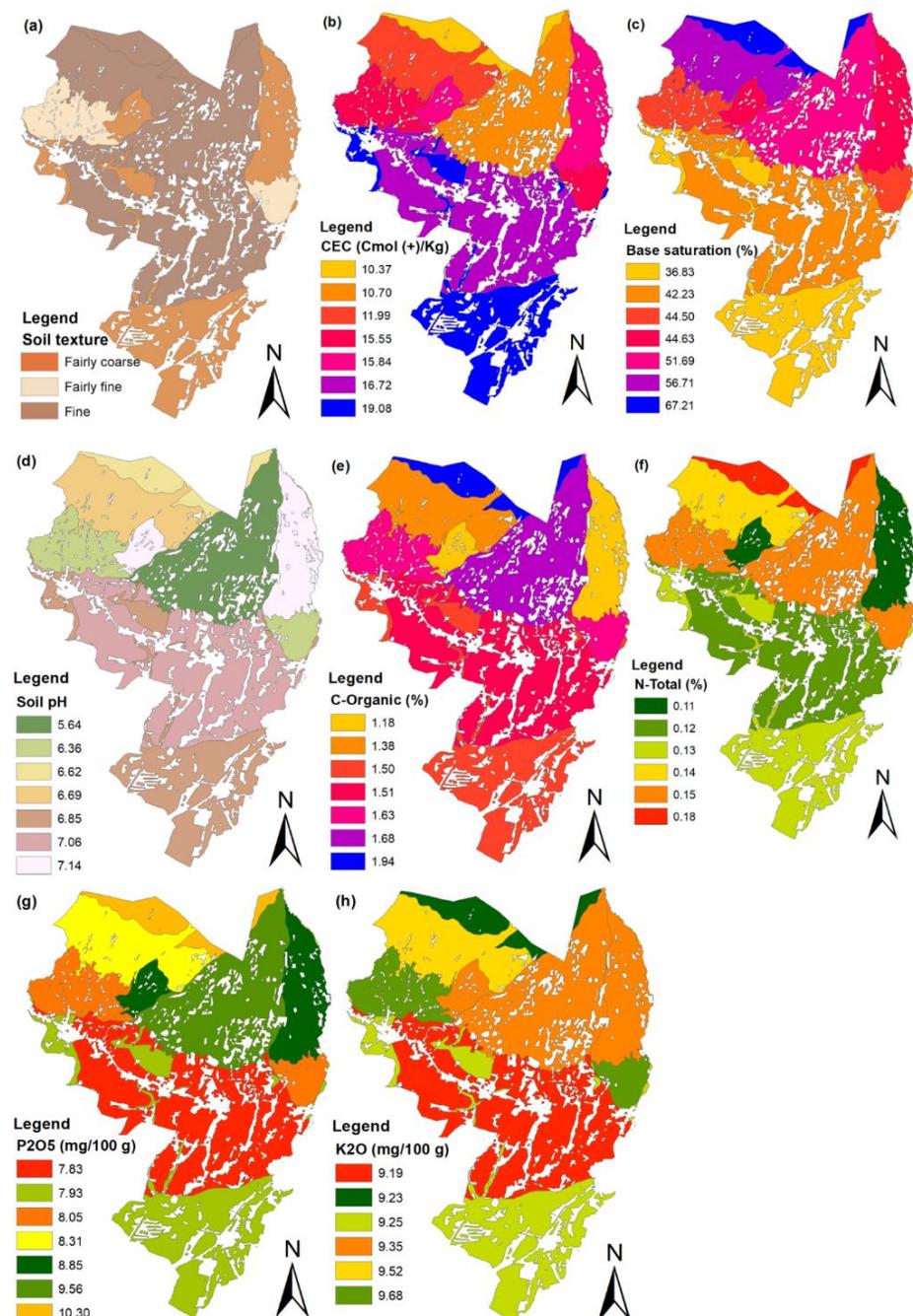


Figure 6. Physical and Chemical Soil Characteristics: a) Texture b) CEC, c) Base Saturation, d) pH, e) C-Organic, f) N-Total, g) P₂O₅, h) K₂O.

This also corresponds to the land conditions at the research location, which have low c-organic and CEC values, meaning the K reserves or stores are low. Another factor leading to low K values is the intensity of processing and fertilization. Fertilization needs to be balanced, with the extraction of biomass, especially organic material, and appropriate timing also needs to be considered, so that fertilizer absorption occurs optimally (Hofmann *et al.*, 2024). If a citrus plant lacks at least 16% of the K element, the leaves will fall off, and the fruit will also fall before it is ripe.

3.3. Suitability Analysis

3.3.1. Actual Land Suitability

Actual land suitability was assessed from the current field conditions. Land suitability evaluation was conducted using a method that matched land characteristic parameters with the growing condition criteria for citrus. The results show that the actual land balance classes for citrus crops (Citrus sp.) in the research area are marginally suitable (S3) and not suitable (N) (Table 4). The map of actual land suitability distribution in the research area is shown in Figure 7.

Table 4. Actual Land Suitability.

| Land Unit | Actual Land Suitability | | | Area | |
|-----------|-------------------------|------------------|--|----------|-------|
| | Class | Sub-Class | Limiting Factors | Ha | % |
| 1 | S3 | S3 na2&3,eh2 | Available nutrients and erosion hazard | 2.441,61 | 10.59 |
| 2 | N | N eh2 | Erosion hazard | 1.063,37 | 4.61 |
| 3 | S3 | S3 na2&3,eh2 | Available nutrients and erosion hazard | 2.661,40 | 11.54 |
| 4 | S3 | S3 rc2,na2&3,eh2 | Rooting condition, available nutrients, and erosion hazard | 2.189,93 | 9.49 |
| 5 | S3 | S3 na2&3 | Available nutrients | 4.092,15 | 17.74 |
| 6 | S3 | S3 na2&3 | Available nutrients | 6.333,62 | 27.46 |
| 7 | S3 | S3 na2&3 | Available nutrients | 4.283,57 | 18.57 |

Land unit 1 covers an area of 2,441.61 ha (10.59%) and unit 3 an area of 2,661.40 ha (11.54%), and includes subclass S3 na2 & 3, eh2, with the main limiting factors being P₂O₅, K₂O, and erosion hazard. Land unit 2, covering an area of 1,063.37 ha (4.61%), includes subclass N eh2, with the main limiting factor being erosion hazard. Land unit 4, covering an area of 2,189.93 ha (9.94%), includes subclasses S3 rc2, na2 & 3, and eh2, with the main limiting factors being root condition, P₂O₅, K₂O, and erosion hazard. Land units 5, 6, and 7, with a total area of 14,709.34 ha (63.77%), include subclass S3, with the main limiting factors being P₂O₅ and K₂O.

2. Potential Suitability Weighting Using AHP and Determination of the Resolution Priorities

The study examines appropriate locations for citrus agriculture using the AHP approach. Table 5 shows the relevance of the main agroecological and environmental elements that impact citrus cultivation, as suggested by Hosen *et al.*, (2025) on dragon fruit. Climate characteristics such as rainfall have the greatest impact (18 %), followed by elements such as drainage (15 %), temperature (16 %) and soil texture (12 %). Erosion hazard (4%) has minimal impact. According to Sadiq *et al.* (2025), a CR (consistency ratio) value of less than 0.1 indicates a high level of reliability. In this study, the consistency index (CI) was used to assess crop field suitability. The resulting CR score was lower than 10% (8.91%), indicating that decision-makers have effectively prioritized factors, resulting in precise and desirable results. This demonstrates the efficiency of the AHP technique in rationally allocating weights to various factors within a multi-criteria framework.

Table 5. AHP Analysis Results for Citrus Land Suitability Assessment.

| | Temperature | Rainfall | Drainage | Texture | ERD | N | CEC | P ₂ O ₅ | K ₂ O | EH | CWI | Consistency |
|-------------------------------|-------------|----------|----------|---------|------|------|------|-------------------------------|------------------|----|------|--|
| Temperature | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 0.16 | CI = 0.13280 RI = 1.49 CR = CI/RI = 0.089129 |
| Rainfall | 0.50 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 0.18 | |
| Drainage | 0.50 | 0.50 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 0.15 | |
| Texture | 0.50 | 0.50 | 0.50 | 1 | 2 | 3 | 3 | 3 | 3 | 4 | 0.12 | |
| ERD | 0.50 | 0.50 | 0.33 | 0.50 | 1 | 3 | 3 | 3 | 3 | 5 | 0.12 | |
| N | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 1 | 3 | 2 | 2 | 2 | 0.07 | |
| CEC | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 1 | 2 | 3 | 2 | 0.06 | |
| P ₂ O ₅ | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.50 | 0.50 | 1 | 2 | 2 | 0.05 | |
| K ₂ O | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.50 | 0.33 | 0.50 | 1 | 2 | 0.04 | |
| EH | 0.33 | 0.25 | 0.25 | 0.25 | 0.20 | 0.50 | 0.50 | 0.50 | 0.50 | 1 | 0.04 | |

Note: CEC: Cation Exchange Capacity; ERD: Effective Rooting Depth; EH : Erosion Hazard; CWI: Cumulative Weight Index

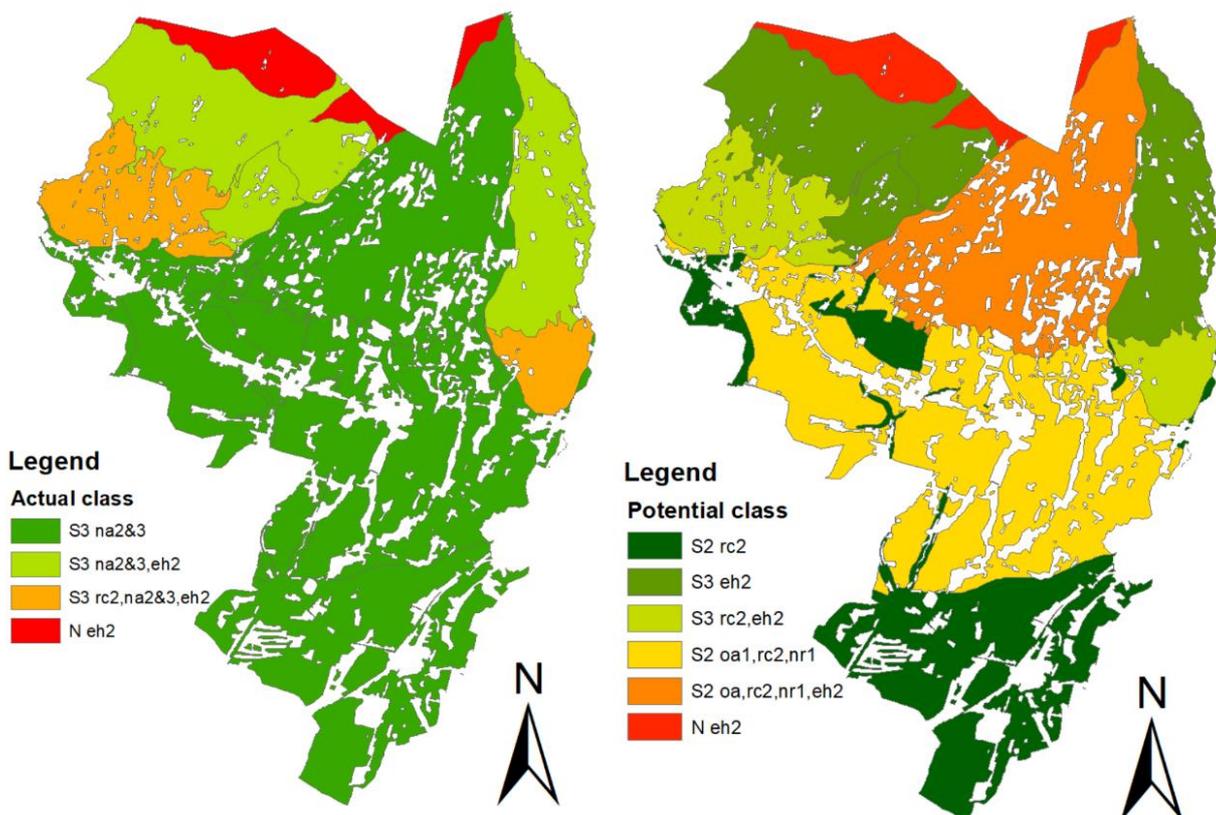


Figure 7. Map of Land Suitability Distribution: a) Actual, b) Potential.

Table 6. Potential Land Suitability Assessed by AHP and Improvement Efforts.

| Land Unit | Actual land suitability | Limiting factors | Improvement efforts | Potential land suitability by AHP |
|-----------|-------------------------|---|---|-----------------------------------|
| 1 | S3 na2&3,eh2 | - P ₂ O ₅ - K ₂ O - Erosion Hazard | - Apply fertilizer - Apply fertilizer - Terrace the land | S2 |
| 2 | N eh2 | - Erosion Hazard | - Terrace the land | S3 |
| 3 | S3 na2&3,eh2 | - P ₂ O ₅ - K ₂ O - Erosion Hazard | - Apply fertilizer - Apply fertilizer - Terrace the land | S3 |
| 4 | S3 rc2,na2&3,eh2 | - Soil Depth - P ₂ O ₅ - K ₂ O - Erosion Hazard | - Mound the soil for plants - Apply fertilizer - Apply fertilizer - Terrace the land | S2 |
| 5 | S3 na2&3 | - P ₂ O ₅ - K ₂ O | - Apply fertilizer - Apply fertilizer | S2 |
| 6 | S3 na2&3 | - P ₂ O ₅ - K ₂ O | - Apply fertilizer - Apply fertilizer | S2 |
| 7 | S3 na2&3 | - P ₂ O ₅ - K ₂ O | - Apply fertilizer - Apply fertilizer | S1 |

Actual land suitability can be upgraded to potential land suitability by considering the AHP analysis after making improvements. Potential land suitability is a condition resulting from the evaluation and improvement of actual land suitability. Improvements can be effected by considering economic aspects and specific conditions, together with the needs of the plants to be cultivated. A distribution map and description of potential land suitability classes are shown in Figure 7 and Table 6, respectively.

Soil quality in the study area is defined by P₂O₅ and K₂O levels, as well as by erosion hazards and soil depth limitations in some areas. The suitability evaluation results indicate that most areas are suitable for citrus production (Figure 7), with 18.57% being highly suitable (S1), 65.28% being moderately suitable (S2), and 16.15% being moderately suitable (S3). To improve soil health and citrus yields, organic fertilizer should be applied, erosion reduced, drainage improved, and loosening techniques employed. Fertilizer should be applied at a total rate of 5 tons/ha, in 3-4 stages. The use of terrace benches facing the slope can reduce erosion, and planting elephant grass and similar plants can reduce the loss of soil particles into the air. Building drainage channels 1

meter deep and 2 meters wide will reduce waterlogging and accelerate downward root growth, thereby increasing productivity. From discussions with local farmers, class S3 na2&3 with a fertilizer application recommendation of 1.5 times higher than normal volume would increase orange productivity by 25%.

3.4. Discussion

This study shows that although current citrus land suitability in Agropuro is predominantly moderately acceptable, the AHP-based evaluation indicates that any limitations can be substantially mitigated through prioritized management interventions, leading to meaningful improvements in potential suitability across several land units. According to the AHP and GIS-based suitability analysis, 18.57% of the land area studied was highly suitable; 65.28% moderately acceptable for citrus agriculture, and 16.15% marginally suitable. The AHP-based potential suitability analysis demonstrated acceptable decision consistency ($CR = 0.089 < 0.1$) and identified rainfall (18%), temperature (16%), and drainage (15%) as the most influential criteria, suggesting that targeted interventions (fertilization, terracing, and soil filling) could improve suitability classes from S3/N to S2, S3, and even S1 in selected land units.

Land suitability assessment is a crucial factor in cultivation techniques, as it helps identify the appropriate zone, both for planting locations and management technique (Fu *et al.*, 2025). Land evaluation methods are divided into matching and AHP approaches. It can be inferred that the AHP method has good flexibility and considers various factors, with a high accuracy rate of up to 85% (Agrawal *et al.*, 2024; Negussie *et al.*, 2024; Sadiq *et al.*, 2025). Land evaluation using a mapping model provides accurate information regarding the zoning of growth-inhibiting factors, including both soil characteristics and environment-related ones (Zaniboni *et al.*, 2025). The environment and soil characteristics strongly support the growth and development of citrus productivity (Gizawu Garbaba & Negasa Wolteji, 2024). Environmental characteristics that play a role include erosion hazard, water availability and temperature. Erosion hazards related to soil movement are primarily caused by other environmental and soil characteristics (Dessalegn *et al.*, 2014; Garbaba & Wolteji, 2024). Environmental characteristics include topography, slope percentage, and rainfall, while soil characteristics that influence erosion hazards include the percentage of dominant texture fractions (Nath *et al.*, 2021; Wang *et al.*, 2022; Zhang *et al.*, 2022). It has been reported that gentle slopes ($>3\%$) affect groundwater conditions (Abuzaid & Abdelatif, 2022; Bhandari *et al.*, 2021; Marghmi *et al.*, 2024). Water affects productivity, particularly the quantity of citrus fruit (Baker *et al.*, 2024; Elshahat *et al.*, 2025). Water availability during the flowering period influences the number of flowers produced; in addition, water supports the formation of sucrose, which affects the fruit's sweetness. Studies show that inadequate watering during the fruit-forming phase can cause flower and fruit drop (Xing *et al.*, 2025). Managing land erosion risks with appropriate conservation techniques can increase water infiltration and reduce runoff (Ma *et al.*, 2025). Appropriate conservation techniques, such as terraced benches using grassy border plants, can reduce groundwater loss by 40% (Rijsdijk *et al.*, 2007).

Crucial soil characteristics for citrus productivity include pH and nutrients (nitrogen, phosphate, and potassium). The ideal pH for citrus cultivation is a minimum of 5 and a maximum of 6-7 (Karki *et al.*, 2024). Soil pH correlates with the availability of nutrients, both macro and micro (Cheng *et al.*, 2023; Freidenreich *et al.*, 2022; Ng *et al.*, 2024). Sufficient nitrogen can be obtained from rainwater, irrigation water, and inputs in the form of inorganic fertilizers (Li *et al.*, 2024; Nuru *et al.*, 2025; Wang *et al.*, 2022). In the research area, nitrogen was not a limiting factor for citrus cultivation, but phosphate and potassium. Phosphate and potassium are mostly present in the soil at high total concentrations but low availability. Phosphate is available at a soil pH of 6.5-7.5, but below or above this range it will be bound by cations such as iron (Fe^{2+}), aluminum (Al^{3+}), magnesium (Mg^{2+}) or calcium (Ca^{2+}) (Bao *et al.*, 2024; Jerand *et al.*, 2016; Madsen, 2019; Zhu *et al.*, 2024). The role of phosphate in horticultural crops is vital in increasing sugar content in citrus and influencing fruit ripening time. Phosphate fertilization recommendations are based on field conditions, with most phosphate values in the low category (Frick *et al.*, 2025). For citrus cultivation, it is necessary to add P fertilizer such as SP-36 at 157.20 kg/ha/plant. Phosphate fertilizer is applied based on plant age: if the plant is 0-3 years old, apply 3-4 times; at 3-4 years old, apply 2-3 times; and at > 4 years old, apply twice per year. Potassium nutrients at the research location are categorized as low, so 495.75 g/plant is needed; at medium nutrient status, 458.72 g/plant is needed. The addition of potassium nutrients also depends on plant age: for plants aged 0-2 years, 3-4 times; for those aged 2-3 years, 3 times; and at age 3-4 years, twice per year (Choudhary *et al.*, 2024). Future research is recommended to examine land suitability at the varietal or clone level for specific crops, such as citrus varieties or clones, such as Semboro, tangerines (SoE, Tejakula, Monita Agrihorti), Siamese oranges (Pontianak, Madu), and new varieties such as Karisma Agrihorti, which produces sweet fruit with yellow flesh.

4. Conclusion

This study conducted land suitability assessments for citrus cultivation in a complex mountainous region of Argopuro by integrating AHP and GIS techniques. According to the AHP and GIS-based suitability analysis, 18.57% of the land area studied was highly suitable; 65.28% moderately acceptable for citrus agriculture, and 16.15% marginally suitable. The primary constraints of the soils are poor nutrient content and root condition, and erosion risk. To increase productivity, management measures should include the application of organic matter, inorganic fertilizers, and plant-mounding soil, and enhancement of terraced land. Incorporating organic matter such as compost, crop waste, or green manure will greatly increase soil fertility by improving nutrient retention, soil structure, and bacterial activity. However, inorganic fertilizers are also required to fill certain nutritional shortages, notably for macronutrients such as phosphorus and potassium. Strategic fertilizer application promotes maximum plant development and yields. Additionally, adding mounding soil for plant systems, such as surface or subsurface drains, aids in the removal of surplus water, promotes soil aeration, and fosters root growth.

In conclusion, the study emphasizes the need for evaluation in making educated land use decisions. Expert judgment may impact the weighing procedure, yet AHP remains an excellent multi-criteria decision-making tool. The combination of AHP and GIS proved useful in determining land suitability for citrus growing in the region. It is hoped this review will improve land use planning, encourage better management practices, and boost citrus output in the region. The findings can support food security, particularly for horticultural crops such as citrus fruits, thus fostering sustainable agriculture.

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Author Contributions

Conceptualization: Basuki, B., Rizaldi, Z. F.; **methodology:** Basuki, B., Rizaldi, Z. F., Sari, V. K.; **investigation:** Basuki, B., Rizaldi, Z. F.; **writing—original draft preparation:** Basuki, B., Sari, V. K.; **writing—review and editing:** Basuki, B., Sari, V. K., Romadhona, S.; **visualization:** Basuki, B. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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