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Surface Soil Carbon Stocks and Fertility Status of Andisols Under Different Management Practices in Vegetable Cultivation in the Volcanic Highlands of Mount Kerinci

Henny H.[1*], Rahmi Dianita[2,3], Yun Alwi[3], Itang Ahmad Mahbub[1]
[1]Department of Agroecotechnology, Faculty of Agriculture, Jambi University, Jambi, Indonesia
[2]BlasTS Center of Excellence, Jambi University, Jambi, Indonesia
[3]Laboratory of Crops and Forages Science, Faculty of Animal Husbandry, Jambi University, Jambi, Indonesia

ABSTRACT

Andisols are known to hold the highest soil carbon stocks among mineral soil types; they are generally found in highlands, fertile, and suitable for vegetable horticulture. Cultivation practices can deplete soil organic matter, thereby reducing carbon stocks and soil fertility. This study aims to examine the impact of land-use intensity and its management in vegetable cultivation on surface carbon stocks and fertility status of Andisol in the Kayu Aro Barat District, Kerinci Regency. A survey method was employed, with observation points and soil samples selected via purposive random sampling. Soil surface carbon stock were estimated using data on soil organic carbon, bulk density, and soil volume at a depth of 0-30 cm. Soil fertility was assessed based on organic carbon concentrations and chemical properties, following the Technical Guidelines for Soil Fertility Evaluation from the Bogor Soil Research Institute. Surface soil carbon storage ranged from 73.94 to 129.11 Mg/ha, with fertility status ranging from low to high. High soil fertility and surface carbon stock were more prevalent on flat terrain that was intensively cultivated with higher inputs of manure, high-dose chemical fertilizers, and dolomite lime. Conversely, low soil fertility and lower carbon storage were observed on hilly terrain regardless of whether cultivation was intensive or non-intensive where inputs were similar but lacked dolomite. To maintain or enhance soil fertility and carbon stocks and to preserve the role of volcanic highlands in mitigating soil carbon loss and global warming, it is crucial to educate farmers on adopting soil management practices that align with soil characteristics and crop requirements.

KEYWORDS: soil carbon stock, organic fertilizer, volcanics soil, soil ameliorant, soil quality

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Corresponding Author:
Henny H.

1. INTRODUCTION

Soil plays a crucial role in mitigating global warming through the sequestration of atmospheric CO_2 by the vegetation growing upon it (Kabato et al., 2025). Globally, soil represents the largest terrestrial carbon reservoir, with 2,400 Gt of carbon stored at a depth of 0-2 m, predominantly in forest soils (30%) and grasslands (30-35%) with a smaller proportion found in agricultural lands (15%). In humid tropical regions (such as Indonesia), soil carbon stocks range from 5 to 750 tons per hectare within the 0-30 cm depth (Blanfort et al., 2026). Drylands store between 20 and 300 ton of carbon per hectare within the 0-100 cm soil depth; this carbon is primarily concentrated in the top 0-30 cm layer, while the amount of carbon at depths exceeding one meter is negligible or virtually non-existent (Agus et al., 2011). The estimated total carbon stock in the topsoil (0-30 cm) for mineral soils in Indonesia is 9.9 ± 0.4 Gt C, with an average carbon content of 58 ± 2 ton/ha; the highest values are observed in Andisols (94 ± 2 ton/ha) (Minasny et al.,

2017). Andisols are volcanic soils that store more than 5% of the global soil organic carbon, despite covering only about 1% of the Earth's land surface (Delmelle et al., 2025). With an average carbon stock of 25.4 kg/m² in both temperate and tropical regions, Andisols are recognized as having the highest soil carbon sequestration capacity among all mineral soil types (Batjes, 2014).

Andisols play a crucial role in maintaining agricultural productivity in mountainous regions worldwide, a function that is highly dependent on how they are used and managed (Mora-Motta et al., 2025). Land-use activities for agriculture tend to lead to a loss of soil organic carbon, which serves as an indicator of a serious threat of land degradation (Demenois et al., 2026). Soil organic carbon in agricultural land is strongly influenced by various agronomic practices and cropping systems (Bohoussou dkk., 2025). Most Andisols are located on sloping terrain with high rainfall, making them highly susceptible to erosion, which can lead to a drastic decline in soil fertility (Perret and Dorel, 1996). Erosion, in Indonesia primarily caused by water, is one of the most widespread and severe forms of soil degradation. It carries away the soil organic matter and nutrient-rich topsoil that is essential for plant growth (Warui, 2024). Climate change trends, driven by rising global temperatures, exacerbate the loss of carbon stored within the soil (Abbas et al., 2020). In other words, the impact of human activity on land can transform soil from a net sink into a net source of greenhouse gases (Arevena et al., 2025; FAO, 2017). Managing soil as a factor of production, while simultaneously leveraging its role in climate change mitigation, requires cultivation practices that maintain soil fertility and productivity, while enhancing soil carbon sequestration and reducing CO2 emissions (Gworek dkk., 2026).

In Indonesia, Andisols serve as a primary source of income for communities in nearly all highland vegetable-producing hubs (predominantly composed of young volcanic soils in black to brownish-black color due to their high content of organic matter and non-crystalline minerals, and are largely found on sloping drylands (Sukarman et al., 2020). Agricultural practices on these dryland Andisols have been in place for a long time (>100 years) and appear to have adapted to the specific characteristics of these soils (Anda et al., 2021). To achieve optimal economic crop performance while minimizing nutrient loss from the soil-plant system, the evaluation of soil fertility becomes a crucial and essential aspect of soil management (Yadav et al., 2023).

Kerinci Regency, situated in the volcanic highlands of Mount Kerinci, serves as a hub for vegetable production (particularly potatoes) in Jambi Province (BPS Kerinci Regency, 2025). Much of the land in this area is classified as moderately suitable (S2) for potatoes, and marginally suitable (S3) for cabbage, chili peppers, and tomatoes. The primary limiting factors include nutrient retention (specifically low base saturation) as well as soil pH levels ranging from acidic to slightly acidic, and the risk of erosion. Slopes ranging from 3 to 30 percent, characterized by undulating to hilly topography, further constrain highland vegetable farming in the region (Henny et al., 2011a). Current land-use practices generally involve conventional farming, where planting ridges are oriented across contour lines. Furthermore, cropping patterns, typically potato-based vegetable rotations, rely on excessive applications of chemical fertilizers and pesticides, without adequate supplementation of organic fertilizer or lime to correct soil acidity. Since 2012, due to labor shortages, nearly all farmers have shifted to using tractors for land preparation (Henny et al., 2024). Previously, land preparation was carried out manually through a local practice known as "malir" (a method involving the use of a hoe to till the soil while simultaneously incorporating crop residues from the previous harvest).

This study aims to examine the impact of land-use intensity and its management in vegetable cultivation on surface carbon stocks and fertility status of Andisol in the Kayu Aro Barat District, Kerinci Regency. The results are intended to serve as a reference for farmers, land users, and relevant authorities in maintaining soil quality and ensuring the sustainability of Kayu Aro Barat District as a hub for highland vegetable production in Kerinci Regency, while simultaneously contributing to the enhancement of soil carbon stocks and the mitigation of global warming.

2. MATERIALS AND METHODS

This study employed a survey method on highland vegetable farms in Kebun Baru Village, Kayu Aro Barat District, Kerinci Regency. Geographically, the village is situated between 101°11'50"-101°15'44" East Longitude and 1°50'45"-1°42'50" South Latitude, at an elevation of 1,600 m above sea level. The local climate is classified as Type A (very wet, Q = 0.0787) according to the Schmidt and Ferguson climate classification system, with an average annual rainfall of 1,923.6 mm (160.3 mm/month), an average temperature of 20.3 °C, and an average humidity of 91.4%. The topography of the area ranges from flat to sloping or hilly (with a slope gradient of 0–30%), and the soil is predominantly classified as Hapludands (Henny et al., 2024).

Most farmers till the soil using a Kubota L3608 tractor (weighing 1.115 tons) equipped with a KRX164-type rotary tiller. The soil is tilled through 3-4 passes of the tractor, following an irregular pattern. The rotary tiller operates using power from the tractor's power take-off, allowing the soil to be turned over and pulverized simultaneously. This tillage practice results in a very fine soil with tillage depth of 30-40 cm. Potatoes and other vegetables (such as chili peppers, shallots, cabbage) are planted on ridges constructed in the same direction as the land's slope. Input usage varies among farmers: manure is applied at rates of 0.2-1 ton/ha, while chemical fertilizers, specifically N:P:K:S (15:15:15:10) are used at 200-1,000 kg/ha, supplemented by 50-500 kg of Urea, 40-200 kg of ZA

(ammonium sulfate), 40-500 kg of SP-36, and 50-400 kg of KCl per hectare. Manure is applied after land preparation along the planting rows on the ridges, while chemical fertilizers are applied at the time of planting and subsequently in split doses based on the crop's age or growth stage. Farmers with greater financial means use larger quantities of both manure and chemical fertilizers, and also employ chemical pesticides to control pathogens, spraying every 3-5 days at doses exceeding the recommendations provided on the product labels. Some farmers use dolomite to manage pathogen outbreaks, specifically targeting late blight (caused by *Phytophthora infestans*) and wilt disease (caused by *Fusarium oxysporum*) in potatoes. Dolomitic lime is applied once symptoms of pathogen infection appear. Observations and topsoil sampling (at a depth of 0-30 cm) were conducted at nine locations selected via purposive sampling, encompassing flat (F), wavy (W), undulating (U), and hilly (H) terrain, with corresponding slope classes of 0-3, 3-8, 8-15, and 15-30 percent. Land use intensity and its management (LUIaM) were categorized into three levels of intensity: Intensive (I; 2-3 cropping cycles and two tillage operations per year), Semi-Intensive (SI; 1-2 cropping cycles and one tillage operation per year), and Not-Intensive (NI; 1-2 cropping cycles per year and one tillage operation every two years) (Table 1) (Henny et al., 2024)

Tabel 1. Land use intensity and its management (LUIaM), topography, and type of cultivation for vegetable crops in the volcanic highlands of Mount Kerinci

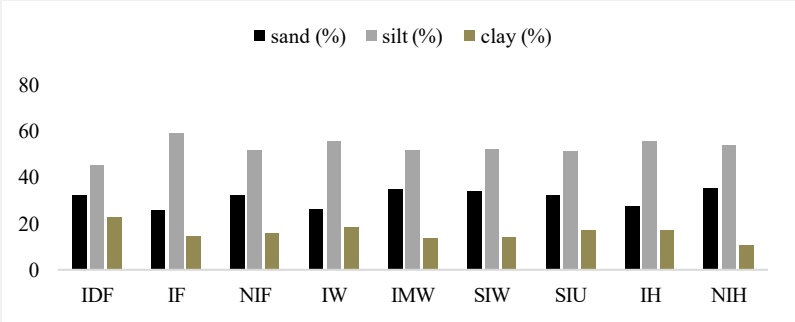
LUIaM/topography	Type of Cultivation
Intensive + dolomite/Flat (IDF)	Cultivated year-round with 2-3 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: 0.8-1 ton/ha of manure plus dolomite for potatoes, high doses of chemical fertilizers
Intensive/Flat (IF)	Cultivated year-round with 2-3 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: 0.4-0.6 ton/ha of manure for potatoes, high doses of chemical fertilizers
Not intensive/Flat (NIF)	Potato cultivation once a year, tractor-plowed once every 2 years, inputs: manure applied (0.2-0.4 ton/ha) for potato, low doses of chemical fertilizers
Intensive/Wavy (IW)	Cultivated year-round with 2-3 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: 0.8-1 ton/ha of manure for potatoes, high doses of chemical fertilizers
Intensive-manure/Wavy (I-MW)	Cultivated year-round with 2-3 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: no or less of manure (<0.2 ton/ha) for potatoes, very high doses of chemical fertilizers
Semi intensive/Wavy (SIW)	Cultivated with 1-2 planting cycles; planted with potatoes and 1-2 tractor-plowed a year; inputs: 0.4-0.6 ton/ha of manure for potatoes, high doses of chemical fertilizers
Semi intensive/Undulating (SIU)	Cultivated year-round with 1-2 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: 0.4-0.6 ton/ha of manure for potatoes, and high doses of chemical fertilizers
Intensive/Hilly (IH)	Cultivated year-round with 2-3 planting cycles; planted with potatoes and tractor-plowed twice a year; inputs: 0.4-0.6 ton/ha of manure for potatoes, and high doses of chemical fertilizers
Not intensif/Hilly (NIH)	Cultivated 1-2 times a year (potatoes once a year); tractor plowed performed once every two years for potato planting; inputs: 0.4-0.6 ton/ha of manure for potatoes, high-dose chemical fertilizers

The data collected include soil organic carbon (SOC) (the Walkley-Black method), particle size distribution (pipette method), and bulk density (measured using soil samples oven-dried at 105°C for 48 hours) (Henny et al., 2024). Data on soil chemical properties at a depth of 0-30 cm encompass pH (extracted with H_2O), total N (Kjeldahl method), P_2O_5 and K_2O (extracted with 25% HCl), available P (Bray-1 method), cation exchange capacity (CEC), and exchangeable bases (Ca, Mg, K, Na) (extracted with NH_4OAc at pH 7.0). Base saturation (%) was calculated by dividing the sum of exchangeable bases by the CEC value. The data were analyzed descriptively using the criteria for soil chemical properties established by the Soil Research Center in Bogor in 1983. Soil fertility status was assessed based on the 1995 Technical Guidelines for Soil Fertility Evaluation from the Soil Research Center in Bogor, utilizing criteria for CEC, base saturation, SOC, P_2O_5, and K_2O (Henny et al., 2025). Soil carbon stock in the 0-30 cm layer (ton/ha) were calculated by multiplying the SOC value (%) by the bulk density (ton/m³) and a soil volume of 3,000 m³/ha.

3. RESULTS AND DISCUSSION

Andisols in vegetable-farming on the volcanic highlands of Mount Kerinci are dominated by the silt fraction (45-59%), with sand (25.67-35.33%) and clay (10.57-22.67%) fractions. Consequently, the soil texture is classified as silty loam, except in flat areas under intensive management that receive dolomite lime (IDF) amendments, the texture is loam—characterized by the lowest silt

fraction (45%) and the highest clay fraction (22.67%) (Figure 1). Other research also indicates that the texture of volcanic soil in the vegetable-growing areas of Mount Kerinci is loam (Anda et al., 2021). Loam is a soil texture formed from a mixture of sand, silt, and clay particles, reflecting the characteristics of each fraction in a balanced proportion; this provides optimal physical and chemical properties for cultivation and plant growth. A higher content of sand and clay fractions makes loam superior to silty loam (Agus et al., 2022). Andisols are soils derived from volcanic ash parent material; they generally possess a medium texture dominated by the silt fraction (Sukarman and Dariah, 2014). Soil texture is an inherent property resulting from the relatively slow weathering of parent rock; it is considered a fundamental soil characteristic that cannot be altered and is generally unaffected by land management practices (McCauley et al., 2005), except on slopes where fine soil fractions (silt and clay) may be removed by surface runoff and erosion (Chen et al., 2024). Most volcanic soils in Indonesia, including those along the Bukit Barisan mountain range in Kerinci Regency, have developed from andesitic-basaltic parent material (Fiantis et al., 2005; Busyra and Firdaus, 2010). Volcanic soils in West Java, which also originate from andesitic and basaltic volcanic ash, have topsoils that are largely dominated by silt, with textural classes of loam and silty loam (Arifin et al., 2022).



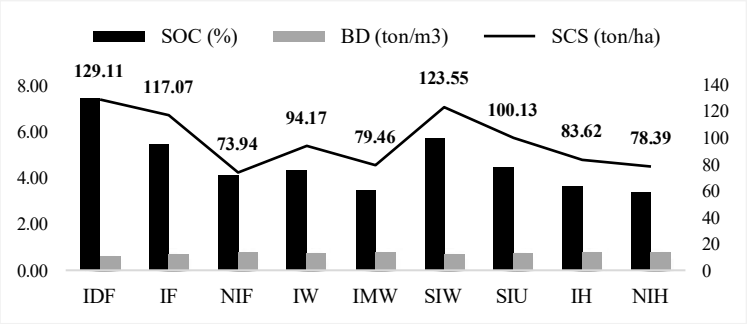
IDF = intenisive+dolomite/flat; IF = intensive/flat; NIF = not intensive/flat; IW = intensive/wavy; IMW = intensive-minimum manure/wavy; SIW = semi intensive/w; SIU = semi intensive/undulating; IH = intensive/hilly; NIH = not intensive/hilly

Figure 1. Particle size distribution of volcanic soils under different vegetable crop management and topographic in the highland of Mount Kerinci

Soil organic carbon (SOC) varies from high to very high (3.12-7.42 percent) and bulk density (BD) is medium (0.72-0.79 g/cm^3) (Figure 2). The high SOC content and moderate BD in these soils are similar to the characteristics of volcanic soils, or Andisols, in Indonesia, which typically exhibit SOC values ranging from 1.24 to 22.46 percent and BD values from 0.37 to 0.90 g/cm^3 (Sukarman and Dariah, 2015). The high SOC and low BD in Andisols compared to other mineral soils are primarily attributed to the formation of non-crystalline materials (such as active Al and Fe, allophane, imogolite, ferrihydrite, and humus-Al/Fe complexes) that possess variable-charge surfaces. Furthermore, the accumulation of organic matter is a dominant pedogenic process in volcanic soils (Dahlgren et al., 2004). In Andisols, this accumulation occurs through the stabilization of soil organic matter (SOM), specifically via processes linked to carbon input and microbial decomposition, as well as shifts in carbon storage capacity throughout soil development (Matus et al., 2014). The formation of humus-rich, non-crystalline materials in the upper layers of volcanic soils contributes to low bulk density by creating a highly porous soil structure, characterized by lightweight and loose aggregates (Nanzyo et al., 1993).

The highest soil organic carbon (7.42%) and the lowest bulk density (0.58 g/cm^3) were observed on flat land under intensive use that received larger quantities of organic fertilizer and dolomite (IDF). This approach effectively mitigates the negative impacts of tillage and the application of high doses of chemical fertilizers (Figure 2). These findings suggest that higher inputs of organic fertilizer and lime can counteract the breakdown of soil aggregates—caused by tillage and soil temperature—thereby controlling the rate of organic matter decomposition and the loss of soil organic carbon (Both and Benites, 2005). Tillage practices, when combined with increased organic fertilizer and lime inputs, reduce the adverseeffects of soil cultivation on soil quality and SOC (Hadaway et al., 2017). Dolomite lime contributes to improved soil aggregation; through the calcium (Ca) and magnesium (Mg) ions derived from dolomite [$CaMg(CO_3)_2$], it helps loosen soil that has a high SOC content. These ions act as intermediaries, bridging negatively charged clay surfaces with the negative functional groups of organic compounds, thereby binding primary soil particles into aggregates (Arsyad, 2010). The application of lime directly influences soil flocculation, aggregation, density, and porosity. Initially, lime promotes the flocculation of soil particles, facilitating the formation of larger particle clusters. Subsequently, H^+ and Al^{3+} ions in the soil are replaced by Ca^{2+} and Mg^{2+} ions; this process enhances particle flocculation, which in turn promotes aggregation and improves soil pore structure reducing macropores while increasing micropores and overall soil porosity (Yunior et al., 2020). At higher lime concentrations, the Ca^{2+} concentration and ionic strength within the soil solution increase, leading to the compression of the electrical double layer and re-triggering the flocculation process (Haynes and Naidu, 1998). Consequently, lime

application improves soil structural properties, including aggregate stability, soil friability, porosity, and infiltration (Wenyika et al., 2025). The application of manure and lime to acidic Andisols results in soil with a significantly higher soil organic matter content compared to soil that has not been limed (Neemisha and Rani, 2022; Alesna and Lina, 2022).



IDF = intenisive+dolomite/flat; IF = intensive/flat; NIF = not intensive/flat; IW = intensive/wavy; IMW = intensive-minimum manure/wavy; SIW = semi intensive/wavy; SIU = semi intensive/undulating; IH = intensive/hilly; NIH = not intensive/hilly

Figure 2. Soil organic carbon (SOC), bulk density (BD), and surface carbon storage (SCS) of volcanic soils under different vegetable crop management and topographic in the highland of Mount Kerinci

The continuous use of chemical fertilizers has adverse effects on the physical properties of soil, such as causing it to harden and reducing its porosity. Hydrochloric and sulfuric acids present in the soil dissolve mineral-rich soil aggregates. The degradation of soil minerals caused by these acids leads to a loss of porosity, resulting in soil hardening or compaction (Widowati et al., 2022). However, the application of larger quantities of organic fertilizer combined with dolomite, even when high doses of chemical fertilizers are used and intensive cultivation is practiced on flat land, can maintain soil SOC levels at 7.42% and BD at 0.58 g/cm³. Conversely, on flat land under intensive cultivation using high doses of chemical fertilizers but only small amounts of organic fertilizer and no dolomite (IF), the SOC is lower (5.42%) and the BD is higher (0.72 g/cm³). Meanwhile, land under non-intensive cultivation, which receives only minimal fertilizer (both organic and chemical) and no dolomite (NIF), exhibits significantly lower SOC (3.12%) and a higher BD value (0.79 g/cm³). This highlights the crucial role of organic fertilizers and lime in preserving soil quality—soil being physically composed of organic matter, mineral components (sand, silt, and clay), water, and air. As an organic substance, manure contains long-chain (polymeric) structures with both negatively charged (carboxyl) and positively charged (amine, amide, amino) functional groups. These facilitate the chemical binding of primary soil particles by linking to the positively charged sites of the clay fraction, thereby forming aggregates (Arsyad, 2010). The soil aggregation process indicates that the clay fraction is crucial for the formation of microaggregates (up to 2.0 mm in diameter), while SOC plays a key role in the formation of macroaggregates (Fernandes et al., 2023). Consequently, the application of manure can increase organic matter content and promote aggregate formation in soils that have become loose due to intensive cultivation, thereby improving porosity and maintaining a loose soil structure with a low bulk density (Rayne and Aula, 2020).

On sloping land, planting on ridges oriented along the slope triggers greater erosion, which leads to the loss or reduction of SOM and a subsequent increase in soil BD. The steeper the slope, the more significant the decline in SOM (Henny et al., 2011b). This is evidenced by substantially lower SOC levels and higher BD values in areas with undulating to hilly topography. Soil loosening and increased soil temperatures resulting from land cultivation also contribute to the loss or reduction of SOM, as decomposition processes accelerate in soils with good drainage and aeration. Consequently, land cultivation and planting on ridges aligned with the slope accelerate erosion, directly causing a decline in SOC (Toth et al. 2025). This condition is reflected in the low SOC levels observed on sloping lands under intensive, semi-intensive, and even non-intensive management. Long-term agricultural cultivation (>100 years) on Andisols in Lembang, West Java, does not lead to the degradation of the soil's physical properties. While tillage does slightly increase BD this is offset by an increase in meso- and micropores, which contributes to a greater water-holding capacity available for plants. The conversion of pine forest into agricultural land appears to enhance soil carbon storage (SCS); within the top meter of the soil profile, the carbon content in agricultural land (25-29 kg C/m²) is higher than that in the pine forest (17 kg C/m²), reflecting a redistribution of organic matter from the topsoil to the subsoil (Anda et al., 2020).

Differences in land management that lead to variations SOC and BD result in soil surface carbon stock (SCS) ranging from 73.94 to 129.11 ton/ha (Figure 1). Volcanic ash soils, which are capable of sequestering large quantities of SOM, consist primarily of stable humic acids. Featuring a humus horizon at least 30 cm deep with an SOC content exceeding 7%, volcanic soils can store more than 100 Mg of organic carbon per hectare (Shoji and Takahashi, 2002). A soil's carbon storage capacity is influenced by the intensity of agricultural management, particularly through the impact of tillage on structural stability and biological activity, specifically the synthesis of compounds such as enzymes and proteins that interact with and bind primary soil particles, thereby influencing aggregate

stability. Thus, soil carbon sequestration serves as a key indicator for managing SOM and protecting SOC (Aravena et al., 2025). Soil carbon stock values were slightly higher (129.11 ton/ha) on IDF land compared to IF land (117.07 ton/ha); both sites are flat, under intensive management, and receive similar inputs. On undulating land (SIW) despite lower organic fertilizer inputs and the absence of liming the SCS value (123.55 ton/ha) was significantly higher than that of other similarly managed, intensive-use sites with comparable topography (94.17 and 79.46 ton/ha), where organic fertilizer use was minimal and chemical fertilizer application was extremely high, often to the point of excess. SCS values were found to be lower on sloping land, regardless of whether the management was intensive or non-intensive. The soil's capacity to store carbon is a primary function of the soil as a key element; the fine mineral fraction has been identified as a determining factor for SOC stabilization across most soil types. SCS is also influenced by climate (particularly temperature and precipitation), topography, and land use and management (Wischmeier et al., 2019).

Agricultural management involving conventional tillage characterized by continuous plowing and leaving the soil exposed can lead to significant carbon loss through CO_2 emissions. This is driven by a combination of increased aeration and the degradation of soil structure resulting from exposure to sunlight (Toth et al., 2025). Conversely, intensive agricultural practices spanning 30-50 years on Andisols in West Java have been shown to increase SCS (Anindita et al., 2021). Research conducted over eight years on Andosols in Kanto, Japan, revealed an increase in SCS in tilled land (10.2 Mg/ha), a figure not significantly different from that observed in soil managed with a rotary tiller (9.0 Mg/ha). Meanwhile, the increase in SOC in areas managed with single-pass plowing or other methods was notably lower, at 6.4 Mg/ha and
5.4 Mg/ha, respectively. Sustainable soil management over a nine-year period has been found to enhance soil carbon accumulation (Higashi et al., 2014). Furthermore, the consistent application of organic fertilizer at a rate of approximately 28 tons/ha/year has demonstrated that carbon levels in the topsoil can be maintained, even in the face of rising temperatures (Toth et al., 2025).

High to very high levels of SOC are accompanied by moderate to very high total nitrogen (N) content (0.42-0.84 percent), a soil pH ranging from acidic to slightly acidic (5.47-6.13), Al exchangeable levels are low (0.03-0.15 me/100g) and not present in all areas (Table 2). Volcanic ash soils accumulate large quantities of organic C and N, the primary components of SOM which serve as a key source of N for plants and provide essential nutrients and energy for soil organisms. Organic fertilizers also contribute to soil N through the decomposition of organic matter by soil microbial activity. Increased use of organic fertilizers, combined with the application of lime, leads to higher total N levels and a more favorable pH. Although the proportion of easily mineralizable organic N within the total organic N pool in volcanic ash soils is relatively small, these soils often accumulate substantial amounts of organic matter containing significant quantities of organic nitrogen. Consequently, volcanic ash soils are generally capable of supplying sufficient mineral N for plant growth (Shoji and Takahashi, 2002). The use of larger quantities of manure and dolomite on intensively managed land can improve soil acidity conditions. In other words, agricultural intensification, which encompasses intensive tillage, the application of organic and chemical fertilizers, and liming can maintain and enhance physical and chemical properties (Shokati and Ahangar, 2014). Soil acidity is primarily attributed to Al^{3+} ions; however, in these vegetable-growing areas, exchangeable aluminum (Al-ea) levels are very low (0.03-0.15 me/100g), undetectable in flat fields, regardless of whether lime was applied (IDF) or (IF, NIF). This indicates that aluminum toxicity is minimal in volcanic soils with an intermediate to basaltic composition (Hidayat and Mulyani, 2002), and that the application of lime can suppress exchangeable aluminum while increasing soil pH. The application of lime can ameliorate soil acidity by raising the pH and simultaneously reducing aluminum (Al) toxicity (Wenyika et al., 2025). The addition of lime and manure significantly increases soil pH and lowers the levels of exchangeable Al in Andisols, thereby improving nutrient availability (Alesna and Lina, 2022).

Table 2. Total N, pH, Al-ea, P_2O_5 and available P, K_2O and available K of soil volcanic under different vegetable crop management and topography in the highlands of Mount Kerinci

LUIaM/topography	Total (%)	NpH	Al-ea (me/100g)	P_2O_5 (%)	Available (ppm)	PK_2O (%)	Available K (ppm)
Intenisive+dolomite/flat	0.84^{vh}	6.13^{sa}	-	98.33^{vh}	16.10^{m}	27.33^{m}	206.67
Intensive/flat	0.63^{h}	5.70^{sa}	-	68.11^{vh}	15.20^{m}	5.33^{vl}	100.33
Not intensive/flat	0.49^{m}	5.47^{a}	-	$61,06^{vh}$	6.60^{vl}	14.33^{l}	46.33
Intensive/wavy	0.65^{h}	5.67^{sa}	0.09	65.89^{vh}	6.40^{vl}	11.00^{l}	100.67
Intensive-manure/wavy	0.49^{m}	5.63^{sa}	0.10	66.06^{vh}	3.70^{vl}	4.33^{vl}	35.00
Semi intensive/wavy	0.68^{h}	5.70^{sa}	0.03	64.61^{vh}	8.50^{vl}	6.67^{vl}	63.33
Semi intensive/undulating	0.63^{h}	5.77^{sa}	0.15	63.17^{vh}	5.80^{vl}	6.00^{vl}	50.00
Intensive/hilly	0.62^{h}	5.53^{a}	0.06	61.16^{vh}	9.83^{vl}	7.00^{vl}	62.67
Not intensive/hilly	0.42^{m}	5.50^{a}	-	62.61^{vh}	5.07^{vl}	9.00^{vl}	80.67

vh = very high, h = high, m = medium, l = low, vl = very low, sa = slightly acid, a = acid

Soil acidity in agricultural land can also be caused by H^+ ions released into the soil solution through the transformation of carbon, nitrogen, and sulfur elements derived from chemical fertilizers (Kunhikrishnan et al., 2016). Consequently, the continuous use of chemical fertilizers negatively impacts soil chemical properties, including the potential for increased soil acidity (Widowati et al., 2022). Long-term, continuous application of NPK and urea fertilizers alters the physical and chemical properties of the soil and lowers its pH, rendering the soil acidic. This decline in pH is more pronounced in areas where only chemical fertilizers are used, whereas in land managed with a combination of chemical and organic fertilizers, the decrease is minimal or does not occur at all (Pal, 2025). The application of organic fertilizers and lime can mitigate the negative impacts associated with the use of chemical fertilizers and soil tillage (Xing et al., 2025). In acidic Andisols, the application of manure and lime results in a significantly higher soil organic matter content compared to conditions where no lime is applied (Neemisha and Rani, 2022).

The total P_2O_5 content is very high (61.06-98.33%) across all sites, whereas the available P content is classified as very low (3.7-9.83 ppm)wi th the exception of sites treated with high doses of manure, both with dolomite (IDF) and without dolomite (IF), which show levels of 16.51 ppm and 15.2 ppm, respectively, falling into the "medium" category (Table 2). This discrepancy very high total P alongside low available P is due to the high P retention (>85%) characteristic of volcanic soils, such as Andisols, where the clay fraction is dominated by nanocrystalline materials (allophane, imogolite, and ferrihydrite). Nevertheless, maintaining the pH of Andisols above 5.0 through the addition of lime or compost can reduce P fixation (Anda et al., 2021). Proper management of Andisols, based on their unique characteristics, can help address soil acidity and increase P availability (Dahlgren et al., 2004). While, total K (K_2O) levels are classified as low to very low, with the exception of IDF land, which is categorized as moderate (27.33%), with available K 46.33-206.67 ppm (Table 2). Potassium (K) is a primary macronutrient essential for overall plant growth, yield potential, product quality, and crop stress resistance. Potato crops require high amounts of K to achieve ideal yield and quality; however, soil K primarily exists in an unavailable form, sequestered within the crystalline structures of minerals such as feldspar and mica (96-99%) (Torabian et al., 2021). In Andisols, potassium is sourced from muscovite and biotite minerals; the presence of these minerals suggests that Andisols in Indonesia possess high potential and actual soil fertility (Sukarman and Dariah, 2015). Potassium is a mobile nutrient, making it highly susceptible to loss through leaching. Furthermore, plants generally show a strong response to potassium; while increased application leads to greater uptake, this does not always translate into higher yields, as plants often engage in "luxury consumption" of K. Consequently, K availability in the soil tends to be low, frequently limited by high leaching rates or fixation by variable-charge clay minerals (Sembiring and Sabrina, 2022).

The cation exchange capacity (CEC) of Andisols in the volcanic highlands of Mount Kerinci ranges from moderate to high (17.04-30.59 me/100 g), while base saturation is low to moderate (28.33-45.00%) with the exception of the IDF site, which exhibits high base saturation (66.67%) and the highest level of exchangeable calcium (17.25 me/100 g) (Table 3). This aligns with the characteristics of Andisols in Indonesia, which have a CEC ranging from 6.5 to 52.0 cmol(+) kg^{-1} (classified as very low to very high), with a mean value of 23.8 cmol(+) kg^{-1}. This parameter is positively correlated with SOC content, meaning that higher organic carbon levels are associated with a higher soil CEC (Sukarman and Dariah, 2015). The application of lime can ameliorate soil acidity by raising the pH, increasing the CEC, enhancing the levels of exchangeable calcium (Ca) and magnesium (Mg), and improving nutrient availability (Wenyika et al., 2025).

Table 3. Cation exchangeable capacity (CEC), base saturation (BS) and bases exchangeable of soil volcanic under different vegetable crop management and topography in the highlands of Mount Kerinci

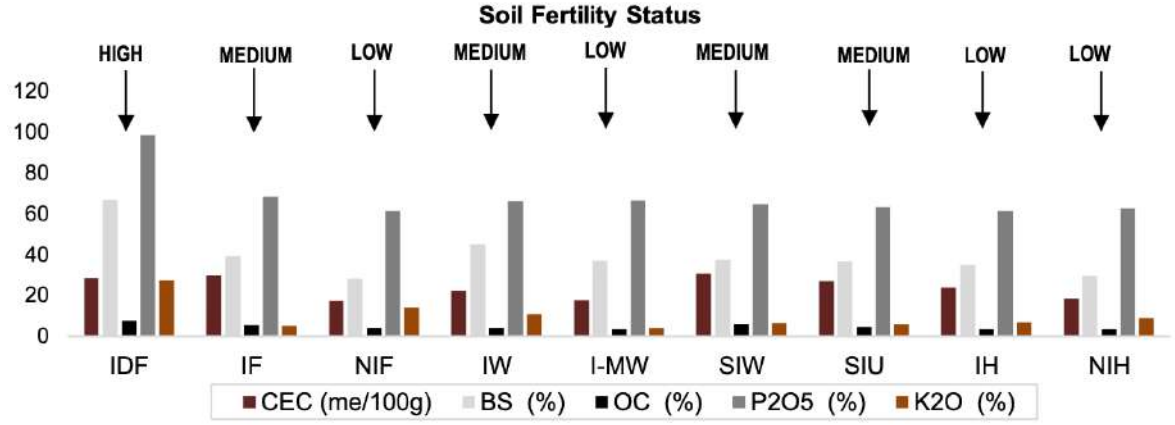
LUIaM/topography	CEC (me/100g)	BS (%)	Bases exchangeable (me/100g)			
			Ca	Mg	K	Na
Intenisive+dolomite/flat	28.51^{h}	66.67^{h}	17.25^{h}	1.32^{m}	16.10^{m}	0.15^{l}
Intensive/flat	29.77^{h}	39.33^{m}	11.74^{h}	0.73^{l}	15.20^{l}	0.11^{l}
Not intensive/flat	17.04^{m}	28.33^{l}	4.75^{l}	0.42^{l}	6.60^{vl}	0.11^{l}
Intensive-manura/wavy	22.12^{h}	45.00^{m}	9.71^{l}	0.93^{l}	6.40^{vl}	0.13^{l}
Intensive/wavy	17.42^{m}	37.00^{m}	5.60^{l}	0.37^{vl}	3.70^{vl}	0.13^{l}
Semi intensive/wavy	30.59^{h}	37.33^{m}	7.73^{m}	0.54^{l}	8.50^{vl}	0.10^{l}
Semi intensive/undulating	26.88^{h}	36.67^{m}	8.98^{m}	0.53^{l}	5.80^{vl}	0.14^{l}
Intensive/hilly	23.79^{m}	35.00^{l}	7.00^{m}	0.48^{l}	9.83^{vl}	0.12^{l}
Not intensive/hilly	18.46^{m}	29.67^{l}	4.27^{l}	0.86^{l}	5.07^{vl}	0.07^{l}

h = high, m = medium, l = low, vl = very low

High SOC (7.42%) in IDF land (Figure 2) with a pH of 6.13 is followed by nutrient content and availability (N, P, K) (Table 2), CEC and BS (66.67%) as well as higher levels of exchangeable bases (Ca, Mg, K, and Na respectively at 17.25; 1.32; 0.38; and 0.15).

me/100g) compared to other fields that did not receive lime input and less organic fertilizer (Table 3). This shows that the organic matter content and soil pH determine other soil chemical characteristics. However, volcanic soils have unique properties, especially high P fixation and higher organic matter content compared to other mineral soils with the clay fraction dominated by nanocrystalline materials (allophane, imogolite, and ferrihydrite), and the colloidal surface dominated by pH-dependent charges (Anda et al., 2020; Dahlgren et al., 2004; Nazyo et al., 1993). Andisol soil colloids are positively charged when the soil pH is below 5.0, while the negative charge of the colloids increases as the soil pH rises above 5.0. Therefore, Andisol soil must be managed by maintaining soil pH above 5.0 through the addition of lime or compost to increase the soil's cation retention capacity (Anda et al., 2021). This emphasizes the crucial role of organic fertilizer and lime in overcoming problems or improving the chemical properties of Andisol soils, a fact that is also seen in volcanic soils in West Java which have been used for agriculture for a long time (>100 years). Intensive use of Andisol soil for horticultural crops combined with the application of organic fertilizer can increase the pH and levels of exchangeable base cations (Ca, Mg, K, Na) while reducing P fixation, so that P availability for plants increases (Anda et al., 2020). Andisol soil on Mount Tangkuban Perahu, West Java, which has been managed with intensive agricultural practices for 30-50 years, also shows improvements in pH, exchangeable base cations, base saturation, and soil carbon stocks, as well as an increase in soil carbon stocks due to stabilization by non-crystalline materials (Anindita et al., 2022). On the other hand, negative impacts due to long-term intensive cultivation characterized by the use of high doses of chemical fertilizers and pesticides without adequate application of organic fertilizer or lime have been observed in volcanic soil used for vegetable farming in West Sumatra, Indonesia; These impacts include soil acidification as well as low levels of carbon in organic matter and exchangeable base cations (Abe et al., 2022).

Based on the soil fertility status evaluation established by the Soil Research Center in Bogor in 1995 which employs "high, medium, and low" categories for parameters including CEC, BS, SOC, P_2O_5, and K_2O, the soil fertility status of vegetable farmland in the volcanic highlands of Mount Kerinci varies from low to high, depending on land-use intensity and management practices (Figure 1). Soil fertility status is classified as "high" if: a) both CEC and BS are high, and more than two of the other variables (SOC, P_2O_5, K_2O) are also high, with no variables falling into the "low" category;
b) both CEC and BS are high, and more than two of the other variables are "medium," with no variables falling into the "low" category; or c) CEC is high and BS is "low," while more than two of the other variables are high, with no variables falling into the "low" category. Any configuration outside of these three combinations is classified as having a "medium" or "low" soil fertility status (Henny et al., 2025). Soil fertility is classified as high only in IDF areas characterized by flat topography and intensive management which receive higher applications of organic fertilizer, high doses of chemical fertilizers, and inputs of dolomite. Conversely, soil fertility is classified as moderate in IW areas (gently sloping or undulating terrain with a 3-8% gradient) that receive similar management but no lime, as well as in IF areas (flat land under intensive management but with lower organic fertilizer inputs and no lime). Meanwhile, soil fertility is classified as low in flat areas that are neither intensively managed nor limed (NIF). Soil fertility is also classified as low in hilly areas, regardless of whether they are under intensive (IH) or non-intensive (NIH) management. It can be concluded that these differences in soil fertility status are primarily driven by variations in CEC, BS, and soil K_2O levels, given that all these sites exhibit high to very high levels of soil organic carbon and very high P_2O_5 content.



IDF = intenisive+dolomite/flat; IF = intensive/flat; NIF = not intensive/flat; IW = intensive/wavy; I-MW = intensive minimum manure/wavy; SIW = semi intensive/w; SIU = semi intensive/undulating; IH = intensive/hilly; NIH = not intensive/hilly

Figure 3. Fertility status of volcanic soil base on criteria of CEC, BS, OC, P_2O_5, and K_2O with different management crop vegetable and topography in the highlands of Mount Kerinci

Variations in the fertility status of Andisols resulting from differences in land-use intensity and management practices are closely linked to the unique characteristics of volcanic soils. These include high SOC content, P fixation, and the presence of soil colloids

with variable (pH-dependent) charges. Furthermore, slope inclination plays a significant role, as it can lead to the loss of topsoil through erosion. Soil analyses from various regions in Indonesia indicate that the natural fertility potential of Andisols ranges from moderate to high (Hidayat and Mulyani, 2002). However, soil fertility may decline or remain low if management practices fail to account for the specific physical, chemical, and mineralogical characteristics of these soils (Anda et al., 2021; Dahlgren et al., 2004). Therefore, to maximize the productivity of Andisol, appropriate management grounded in a profound understanding of their unique properties is essential (Dahlgren et al., 2004).

4. CONCLUSION

Soil surface carbon stocks (0-30 cm) of Andisols under varying land-use intensities and management practices in the vegetable-farming areas of the Mount Kerinci volcanic highlands range from 73.94 to 129.11 ton/ha, with soil fertility levels spanning from low to high. These differences in soil fertility status are primarily driven by variations in cation exchange capacity, base saturation, and soil K_2O levels, given that all these sites exhibit high to very high levels of soil organic carbon and very high P2O5 content. Higher soil fertility and greater soil surface carbon stocks (129.11 ton/ha) are found on flat land that is managed intensively, utilizing higher inputs of manure, chemical fertilizers, and dolomitic lime. Conversely, lower soil fertility and smaller carbon stocks are observed on hilly terrain regardless of whether the land is managed intensively or extensively where inputs are relatively similar but lack the application of dolomitic lime. To maintain or enhance soil fertility and carbon stocks, while supporting the role of the Mount Kerinci volcanic highlands as a hub for vegetable production (particularly potatoes) in Kerinci Regency, and simultaneously contributing to the mitigation of soil carbon loss and global warming it is both essential and urgent to educate farmers and land users on implementing soil management practices that are well-aligned with specific soil characteristics and crop requirements.

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