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Assessment of soil cone index in agricultural land on the slope of Mount Lawu, Indonesia

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Abstract

Soil compaction is a major issue causing a significant threat to agricultural land and food production. Therefore, this research aimed to identify the distribution of soil cone index (CI), assess the impact of variability in sources, determine the key soil features, and provide recommendations for land management. The survey was conducted in Slogohimo Sub-district, Wonogiri Regency, Indonesia, at an elevation of 1,541 feet on Mount Lawu, using a descriptive exploratory and laboratory analysis method. Survey and soil sampling used the ground drill and Dynamic Cone Penetrometer (DCP) at depths ranging from 0 to 30 cm, with a 10 cm interval. The results of CI analysis showed that the condition of soil compaction ranged from high to extremely high, varying between the values of 2.58 MPa and 11.25 MPa. The high CI class covered the largest area of 2,116.83 ha (39.50%), followed by the very high with 1,324.54 ha (24.71%) and the extremely high at 1,918.13 ha (35.79%). The types of soil were also found to significantly affect soil CI. Bulk density and soil texture were positively correlated with CI, while organic carbon and moisture content showed a negative correlation. As a determining factor, the recommendation strategy was to add organic matter and proper land management for CI optimization to a moderate level, thereby supporting land productivity.

1. Introduction

Agricultural land and food production are facing significant issues due to soil compaction caused by land degradation (Carlesso et al., 2019). The compacted soil can disturb roots that penetrate soil until the growth of plants is hampered (Colombi and Keller, 2019). This phenomenon is related to the physical properties of soil, which support growth and plant production because of the ability to influence root penetration, water-holding capacity, drainage, aeration, and nutrient content availability. Among the properties, soil penetration resistance can describe the condition of roots in passing through soil (Colombi et al., 2018). High penetration resistance caused by soil compaction (Alhai, 2021) presents a challenge in tillage and no-tillage agricultural land (Romadhon et al., 2023).

Soil compaction can cause a reduction of pores, impacting air transportation underground (Shah et al., 2017), and is often measured by assessing bulk density and cone index (CI) (Khetsha et al., 2024). Based on the previous research by Mirzavand and Reza (2021), soil tillage is capable of decreasing compaction compared to minimum or the lack of tillage management. However, extended conventional tillage through plowing can negatively affect, leading to increased compaction and a decline in both organic matter and soil organisms (Bogunovic et al., 2018). This tillage has the potential to accelerate compaction due to the reduction of organic matter. In compacted soil, root growth tends to be shorter, causing scattered development to the sides (Zhang et al., 2021). Although proper tillage has the potential to reduce the risk of aggregates, the process is associated with a negative impact in some practices (Liu et al., 2021).

CI is a parameter used to indicate soil resistance to root penetration, measured using a cone penetrometer, which is available in various types such as mechanical, analog, and digital (Priyonggo and Mufidah, 2021). Dynamic Cone Penetrometer

(DCP) is a penetrometer with a standard load to move the cone and penetrate soil. The depth achieved is measured against the number of blows with a standard load, which is recorded in millimeters, and the results are related to the investigated soil parameters (Ampadu, 2015). Because the dynamic equilibrium of the soil is influenced by its natural properties, mineral composition, and the intensity of the soil weathering itself (Hanudin et al., 2025).

The significance of CI analysis is to show soil compaction, which causes negative effects on root penetration alongside the uptake of water and nutrients. Environmental diversity factors such as soils, topography, and management in each different land use will trigger changes in soil characteristics and cause density. This shows the need to analyze various physical and chemical aspects to discover the correlation between CI. Therefore, this research aims to identify soil CI, identify the effect of soil type and topography of mountain slope on density levels, examine the determining factors, and formulate appropriate land management strategies to prevent soil compaction. Mapping actual soil conditions can foster accurate land and environmental conservation (Putra et al., 2025). The methods used were adapted and refined, including the application of DCP test, modification of soil indicators, and Pearson correlation statistical analysis to determine factors and present efficient land management recommendations for farmers, as well as related stakeholders.

2. Materials and methods

2.1. Research area

This research was conducted in Slogohimo Sub-district, Wonogiri Regency, Central Java Province, Indonesia, with 7°82’60.1’’S and 111°18’72.8” E (Fig. 1). Agricultural land in this area was predominantly paddy fields, plantations, moor, and forest with a total area of 5,359.5 hectares (ha) and located on Mount Lawu-slope at about 470 m asl (meters above sea level) or 1,541.99 feet.

2.2. Soil sampling and analysis

Soil sampling was based on land map units from sources of thematic variability, comprising rainfall map (1:25.000) (Fig. 2), soil types (1:25.000) (Fig. 3), slope (1:25.000) (Fig. 4), and land use (1:25.000) (Fig. 5). The diverse rainfall was categorized into three levels, namely low, medium, and high, corresponding to 1,908 mm/year, 2,316 mm/year, and 3,650 mm/year, respectively. The slope was classified into five classe, namely 0–8%, 8–15%, 15–25%, 25–45%, and >45%, while soil types consisted of Inceptisols and Andisols. Land use included forest, plantations, paddy fields, and moors. Subsequently, an overlay of maps from each source of variability was performed to produce the Land Map

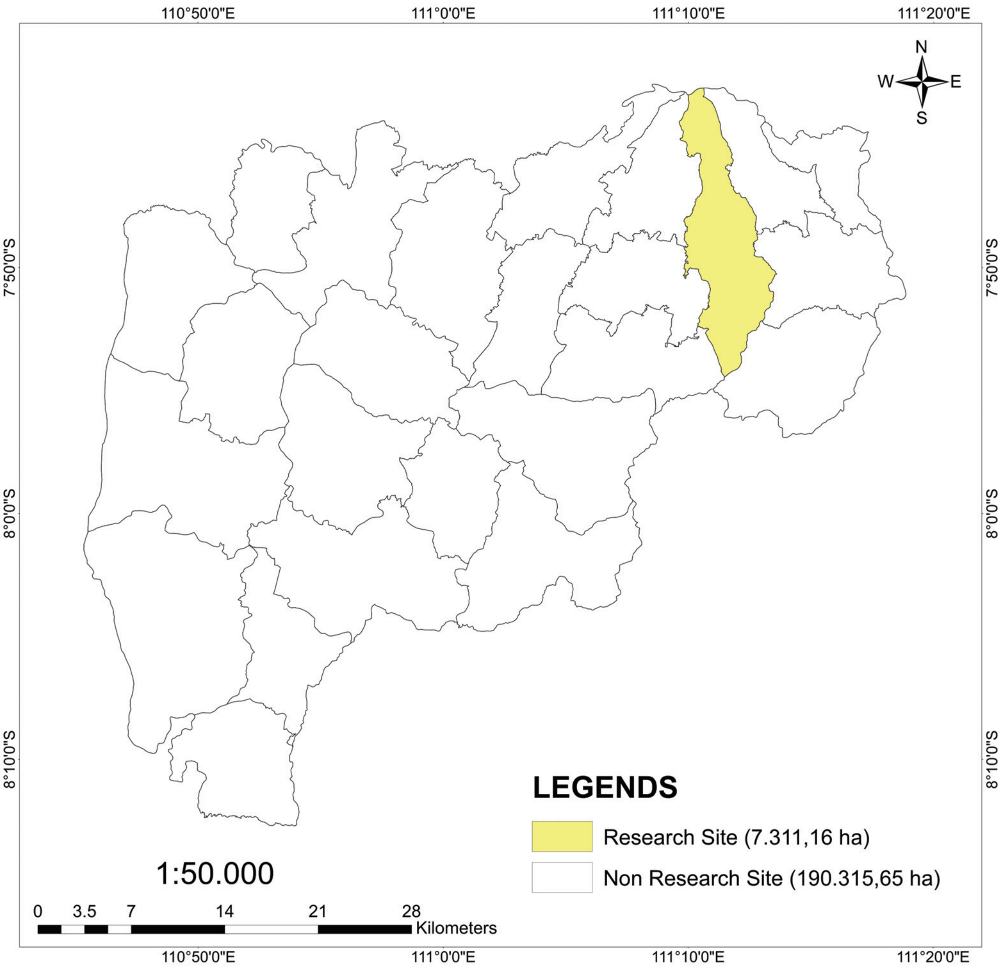

Fig. 1. Research area of Slogohimo

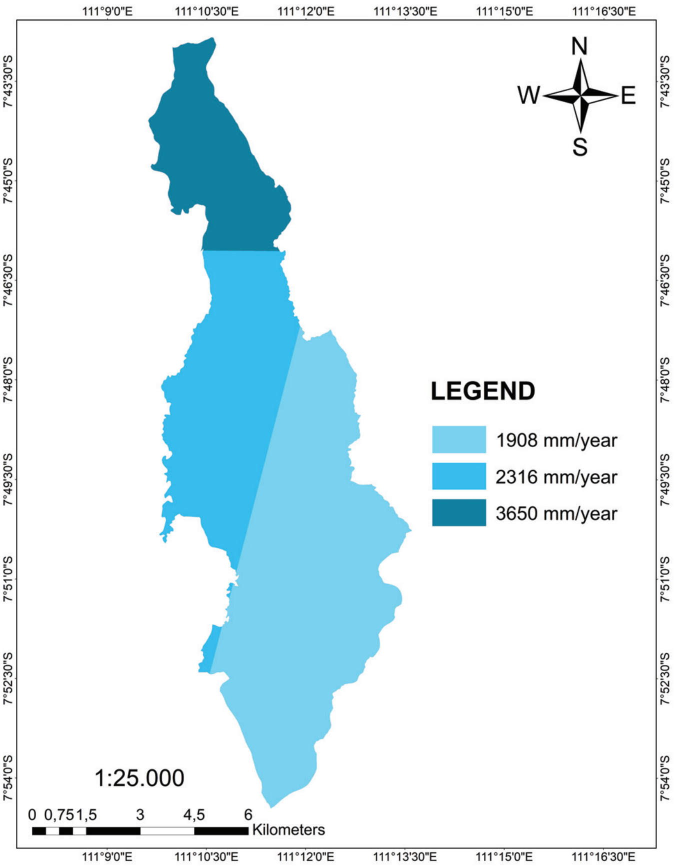

Fig. 2. Rainfall map

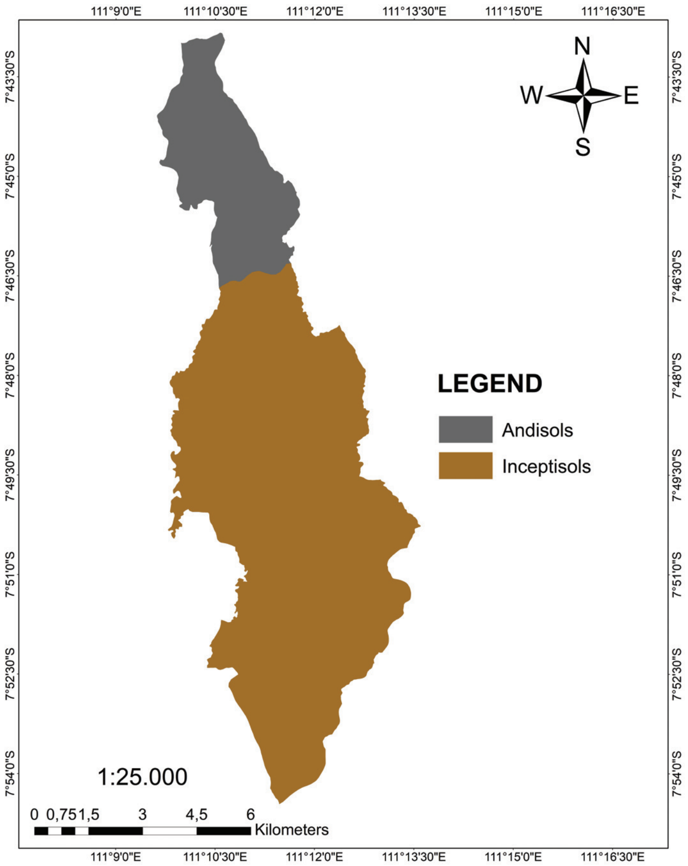

Fig. 3. Soil type map

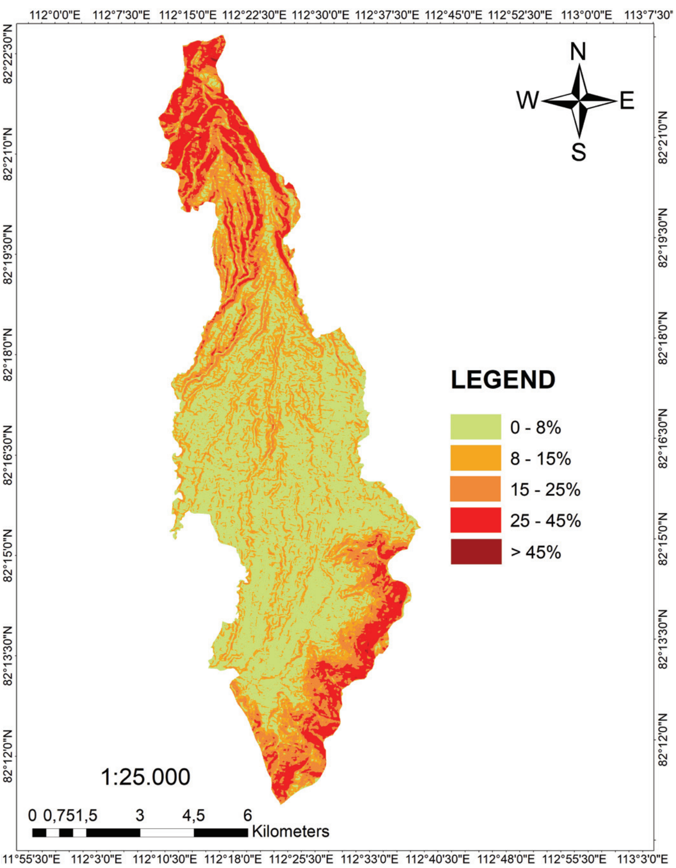

Fig. 4. Slope map

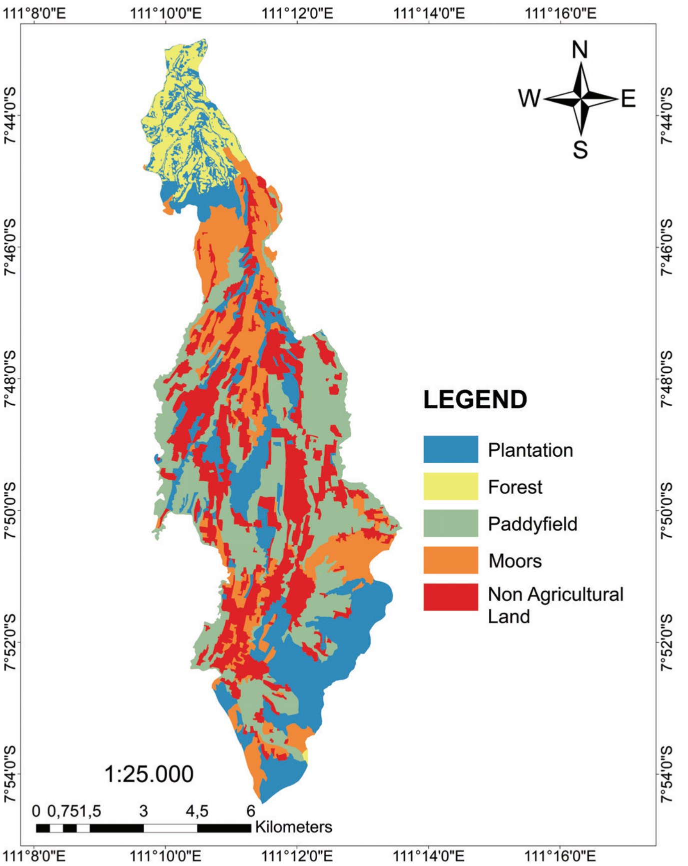

Fig. 5. Land use map

Unit (LMU) map. Based on these sources of variability (Table 1), a total of 17 LMUs with 3 points of repetition in each LMU were identified in research area (Fig. 6 and Table 1).

Field analysis was carried out to assess slope using a clinometer and soil compaction with a DCP. The equipment was set up with an angle cone of 60° (20 mm diameter) and inserted into soil

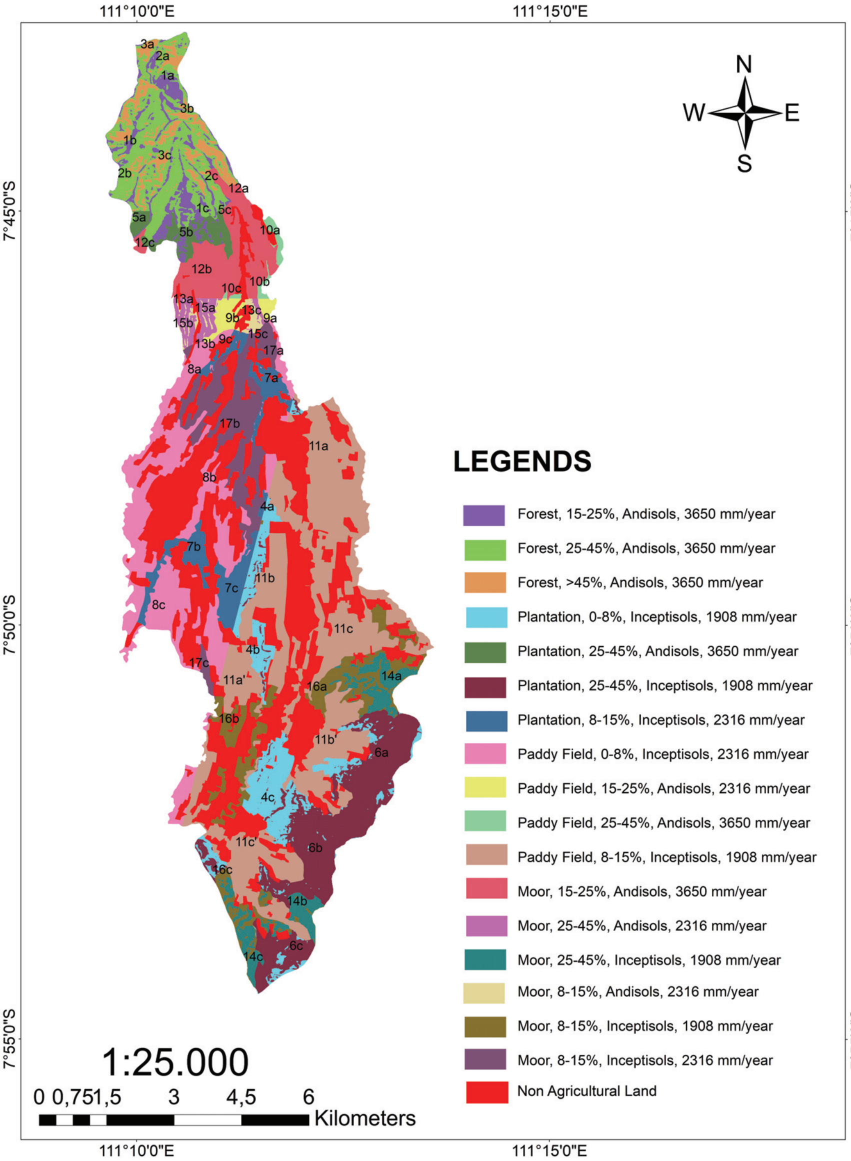

Fig. 6. Map of sampling point in the research area

Table 1
The characteristics of each LMU in Slogohimo sub-district

LMU	Rainfall (mm/year)	Soil type	Slope	Landuse
1	3,650	Andisols	15–25%	Forest
2	3,650	Andisols	25–45%	Forest
3	3,650	Andisols	>45%	Forest
4	1,908	Inceptisols	0–8%	Plantation
5	3,650	Andisols	25–45%	Plantation
6	1,908	Inceptisols	25–45%	Plantation
7	2,316	Inceptisols	8–15%	Plantation
8	2,316	Inceptisols	0–8%	Paddy field
9	2,316	Andisols	15–25%	Paddy field
10	3,650	Andisols	25–45%	Paddy field
11	1,908	Inceptisols	8–15%	Paddy field
12	3,650	Andisols	15–25%	Moor
13	2,316	Andisols	25–45%	Moor
14	1,908	Inceptisols	25–45%	Moor
15	2,316	Andisols	8–15%	Moor
16	1,908	Inceptisols	8–15%	Moor
17	2,316	Inceptisols	8–15%	Moor

at various depths (0–10 cm, 10–20 cm, and 20–30 cm) through repeated drops of an 8 kg from a height of 575 mm (Lee et al., 2019). The disturbed samples were used to analyze specific texture, moisture content, and organic carbon, while undisturbed samples were applied for bulk density evaluation. All samples were dried, where 0.5 mm and 2.00 mm sieves were used for analysis at the Laboratory of Physics and Soil Conservation and the Laboratory of Soil Chemistry and Fertility of Agriculture Faculty, Universitas Sebelas Maret, Indonesia. Soil parameters analyzed using guidelines of Soil Research Institute (*Balittanah*) (2009), included organic C (Walkey and Black method), bulk density (gravimetric method), moisture content (gravimetric method), porosity (pycnometer method), and texture (pipetting method).

2.3. Data analysis

The results of using DCP were measured in millimeters (mm) with the number of standard 8 kg blows, which were converted into MPa units through the following equation (Meshalkina et al., 1995).

$$P = \frac{A}{\pi r^2 d} = \frac{N \times m \times g \times h}{\pi r^2 d}$$

P = Penetration force (MPa),
N = number of blows,
m = mass of standard load (kg),
g = gravity (9.8m/s^2),
h = height of the rod (m),
r = radius of the cone (m),
d = depth of the cone (m).

The collected data from the field analysis process were converted into Mega Pascal (MPa) units as soil penetration resistance class, as shown in Table 2.

Statistical analysis was conducted using SPSS version 26.0, with Analysis of Variance (ANOVA) test to determine the effect of source diversity, consisting of rainfall, slope, and land use, on CI in Slogohimo District. The value used to show significant conditions was p value <0.05, and very significant conditions represented p value <0.01. When ANOVA test showed significant conditions, it was continued with the Duncan Multiple Range Test (DMRT) to determine the difference in values for each dependent variable. Meanwhile, T test was performed to determine the effect of soil type on CI. This research also examined observation indicators that determined CI using Pearson's Correlation analysis to identify a significant relationship between soil properties and CI. Subsequently, linear regression analysis was carried out to determine the direction of the relationship.

Table 2
Soil penetration resistance class

Penetration Resistance	Class
< 0.01	Extremely low
0.01 – 0.1	Very low
0.1 – 1.0	Low
1.0 – 2.0	Moderate
2.0 – 4.0	High
4.0 – 8.0	Very high
> 8.0	Extremely high

Source: USDA (1993)

3. Results and discussion

3.1. Soil physical and chemical properties

Table 3 shows the parameters of supporting soil properties, including bulk density, porosity, texture, moisture content, and organic-C. Bulk density represents the ratio between dry soil weight, volume, and pores. The results of bulk density analysis indicated values ranging from 0.77 g cm^{-3} to 1.25 g cm^{-3}. The highest value of 1.25 g cm^{-3} was obtained at LMU 8, in rice field land use, and a slope of 0–8%. This showed high soil compaction and was intercorrelated with low organic-c content and reduced water absorption. Meanwhile, LMU 2 showed the lowest value of 0.77 g cm^{-3} in forest land use andisols soil type, and a 25–45% slope, with a density of less than 0.9 g cm^{-3} (Yulina et al., 2023).

Soil porosity in agricultural land ranged from 39.54% to 53.39%. In this research, the highest porosity value was shown at LMU 15 (53.39%), a moorland area with a clay texture of 67.89%. Soil with a clay texture has a larger total pore space than other types due to larger micropore space, causing the improvement of water and aeration movement in soil for greater plant growth (Romadhon et al., 2024). In LMU 8, porosity was the lowest at 39.54% with paddy field land use and a slope of 0–8%. Bulk density value affected the porosity with a negative correlation, as shown by the highest volume weight value of 1.25 g cm^{-3}. The number of micropores showed that soil was compacted, causing a reduction in capability of water holding capacity for the plant roots.

Generally, soil texture is determined by comparing the values of silt, sand, and clay. The results showed that clay texture was the predominant soil type at LMU 4, 5, 7, 8, 9, 11, 12, 15, 16, and 17, which were typically used as plantations, paddy fields, and moorland. This texture is characterized by being heavy and moldable during moist conditions, which becomes hard and compact in dry seasons. Low pores in clay soil led to decreased air circulation and relatively slow water conductivity, which hindered water supply to the plants, particularly during dry seasons (Oco et al., 2024). However, when dominated by micropores, as in LMU 15, infiltration rates can still be low. High porosity due to particles on clay is dominated only by micropores, showing potential reduction in the rate of infiltration (Istiqomah et al., 2024).

Clay loam texture was found at LMU 10 and 13, under paddy fields and moorland land use, which were categorized as Andisols. Specifically, LMU 1 and 3, under forest land use, showed a silty clay loam texture with Andisols. Loam texture was shown at LMU 2, 6, and 14 with land use types of forest, plantation, and moor with 25–45% slope classes. Soil with loam or clay textures generally has a higher water-holding capacity due to the larger pore volume.

Table 3
Soil physical and chemical properties

LMU	Bulk density (g cm⁻³)	Porosity (%)	Fraction (%)			Texture class	Moisture content (%)	Organic Carbon (%)
			Sand	Silt	Clay			
1	0.89	49.81	15.84	46.69	37.47	SiCL	19.81	3.58
2	0.77	49.76	27.42	48.12	24.46	L	24.30	2.92
3	1.09	44.85	19.02	50.46	30.52	SiCL	12.78	2.96
4	1.14	47.99	8.64	23.95	67.41	C	12.67	1.80
5	1.03	52.37	10.43	34.00	55.57	C	13.09	2.06
6	1.11	49.13	49.66	37.53	12.81	L	8.51	1.17
7	1.16	47.03	11.25	17.78	70.97	C	13.34	1.34
8	1.25	39.54	13.48	34.85	51.67	C	10.60	1.48
9	1.16	45.07	16.97	35.03	48.00	C	11.56	2.21
10	1.06	50.06	36.60	36.05	27.35	CL	9.07	2.38
11	1.08	50.46	11.28	24.36	64.37	C	12.71	1.27
12	0.96	52.39	11.69	31.98	56.33	C	11.49	2.56
13	1.12	49.43	21.32	41.91	36.77	CL	16.37	1.77
14	1.23	47.32	49.67	36.51	13.82	L	10.37	1.24
15	1.02	53.39	5.68	26.43	67.89	C	7.73	1.38
16	1.12	47.58	9.16	22.78	68.08	C	12.49	2.12
17	1.04	50.00	13.43	35.66	50.91	C	12.90	2.57

Remark: C (Clay); L(Loam); SiCL (Silty Clay Loam); CL (Clay Loam)

Organic-C content varied between 1.17% to 3.58%, with the highest value recorded in LMU 1, characterized by forest land use and slope 16–25%. This area has dense vegetation and litter from decomposed plant debris, which contributes significantly to the accumulation of organic-c in soil. In comparison, the lowest organic-c is found at LMU 6, worth 1.17%, which is associated with plantation land use. The lack of organic elements in soil causes the value of organic-c content to be lower.

The highest moisture content was observed in LMU 2 with forest land use type, 25–45% slope, and Andisols at 24.30%. Previous research reported that soil properties of Andisols showed high moisture content (Istiqomah et al., 2023). LMU 15 has a moorland type with a slope of 8–15% and poses a low moisture content of 7.73%. Insufficient soil moisture content tends to increase resistance to compaction because of limited pore space for water absorption. Long-term intensive tillage can reduce soil moisture content because of soil-turning process (Kurniawan et al., 2023).

3.2. Soil Cone Index (CI)

The CI was measured by DCP Test at the depths of 0–10 cm, 10–20 cm, and 20–30 cm to determine compaction in each layer. The results of ANOVA test showed a significant difference among mean the mean CI value across three soil layers (F-count = 27.594; P-value = 0.000; N = 51. According to Duncan Multiple Range Test (DMRT) results, there was a significant difference between soil layers. The 0–10 cm layer showed highest average of 5.1 MPa, while 10–20 cm and 20–30 cm were statistically equivalent, with values of 2.73 MPa and 1.95 MPa, respectively (Fig. 7).

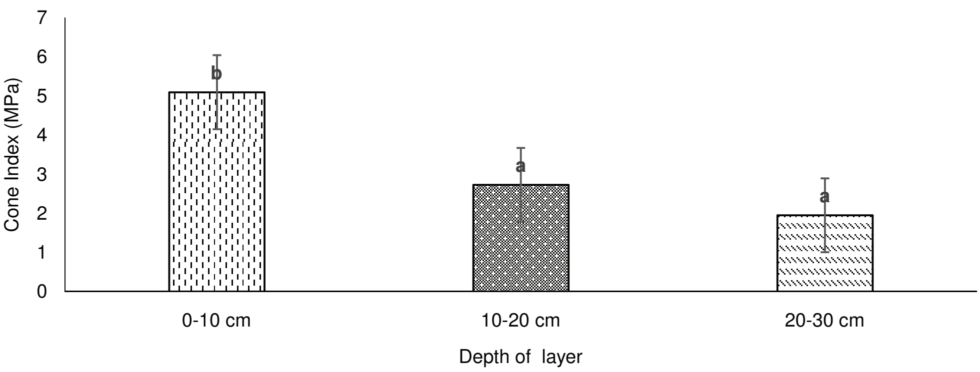

Fig. 7. Average CI of soil at 0–10 cm, 10–20 cm, and 20–30 cm depths
Remark: Numbers followed by the same letter notation indicate no significant difference in DMRT test at the 5% level.

Generally, intensive tillage of the surface layer can cause a decline in organic matter, which contributes to rapid compaction and increased soil density. This is proven by the result of CI in the 0–10 cm layer, which is relatively higher than in 10–20 cm and 20–30 cm layers. In comparison, land management is also carried out on forests at LMU 1, 2, and 3, located in the Girimanik forest, covering 10 hectares. These areas are classified as non-timber production forests with rubber plantations for latex production managed by Wonogiri Province authority (Roziaty, 2020).

CI at the depth 0–30 cm was evaluated to the total depth of the layer compaction. ANOVA test of the source of variation LMU with CI showed that LMU had a highly significant effect on CI (F-count = 13.504; P-value = 0.000; N = 51). The results of Duncan's Multiple Range Test (DMRT) also showed that CI values at a depth of 0–30 cm ranged from 2.58 MPa to 11.25 MPa, representing a high to very high class. As shown in Table 4, LMU 8 indicated as land use type with CI of 11.25 MPa, was significantly different from others. This suggested that the density level in LMU 8 paddy field soil was very dense. Compacted soil has potentially high penetration resistance, causing decreased water infiltration into soil and disturbed plant germination (Yustika and Muchtar, 2016).

According to Kusuma and Yulfiah (2018), soil with a fine texture has a much higher pore percentage and is often not well connected, causing a higher retention capacity. These soil characteristics are found in LMU 8, consisting of 51.67% clay, with a porosity in paddy field percentage of 39.54%, moisture content of 10.60%, and 1.25 g cm^{-3} bulk density. CI values at a depth of 0–10, 10–20 cm, and 20–30 cm are 10.15 MPa, 5.83 MPa, and 20(–30, respectively. This shows that at 0(–10 cm, soil compaction level is very high, which decreases as the depth increases, such as 10–20 cm and 20–30 cm layers. Soil tillage using tractor machinery induces high pressure on soil and can be a source of damage to structure and compaction (Shah et al., 2017).

The lowest CI value was recorded in LMU 2 at 2.58 MPa, categorizing it as high compaction. LMU 2, a forest area with a 25–45% slope and Andisol soil, showed a pattern of decreasing soil density with depth, which ranged from 2.21 MPa (high) at 0–10 cm, to 1.39 MPa (moderate) at 10–20 cm, and 0.70 MPa (low) at 20–30 cm. Furthermore, LMU 2 had the highest soil moisture content at 24.30% due to the high levels of organic matter produced by the decomposition of plant litter. This observation was in line with Wirosoedarmo (2005), who observed that the higher moisture content could reduce water accessibility and plant productivity (Colombi et al., 2018).

In Slogohimo Sub-district, CI is presented as a map (Fig. 8) with three classes, which are represented in different colors. The moderately high is shown in pink with the highest area of 2,116.83 ha, or 39.50% of the total area. This is followed by the red area in high class occupying 1,324.54 ha, or 24.71% of the total area, while the very high is indicated by dark red with an area of 1,918.13 ha, or 35.79%.

Table 4
Soil cone index (CI) in study area

LMU	Cone Index (MPa)	Class of Cone Index
1	4.39abc	Very high
2	2.58a	High
3	3.62ab	High
4	10.50gh	Extremely high
5	3.32ab	High
6	7.10fg	Very high
7	5.37bcde	Very high
8	11.25h	Extremely high
9	6.84de	Very high
10	3.80abc	High
11	3.36ab	High
12	4.67abcd	Very high
13	3.29ab	High
14	5.97cde	Very high
15	7.56ef	Very high
16	9.02fg	Extremely high
17	4.74abcd	Very high

Remark: Numbers followed by the same letter notation indicate no significant difference in the DMRT test at the 5% level.

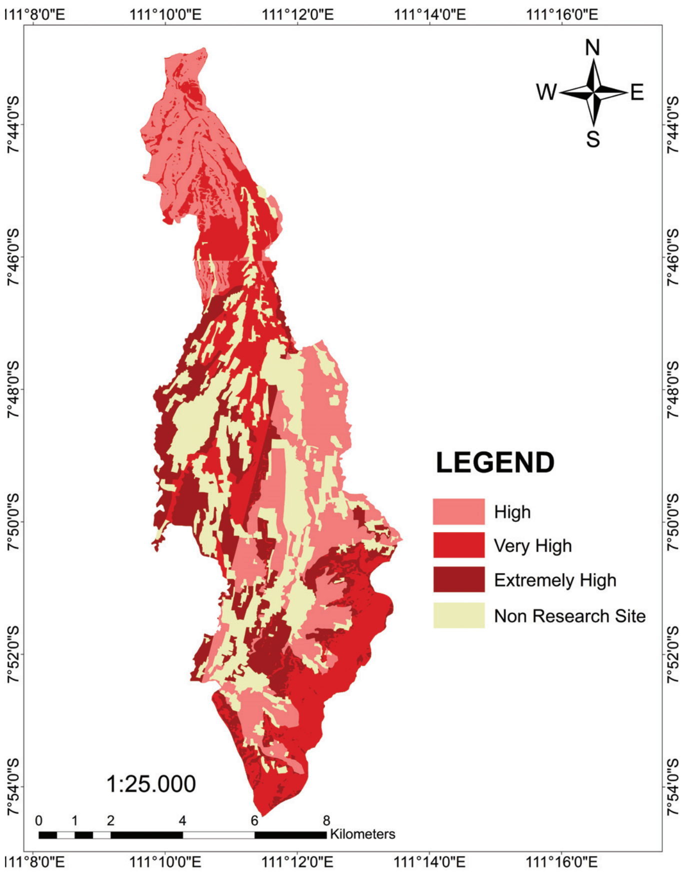

Fig. 8. Soil CI map in research area

3.3. The distribution of CI in Andisols and Inceptisols

The t-test results in Table 5 showed that soil type significantly affected CI (p value = 0.00 < 0.05). Andisols have a lower average bulk density than Inceptisols, indicating loose texture and more porosity. This lower bulk density facilitates root penetration but inhibits the formation of micropores, potentially affecting the availability of water and air to plants. Although the porous nature supports root growth, careful management is required to address issues related to water movement in soil. In comparison, Inceptisols have lower organic-c and a higher bulk density, which makes water and root penetration more difficult (Dewi et al., 2020). According to the DMRT results in Fig. 9, the distribution of CI in Andisols showed that the highest average (7.5 MPa) occurred in LMU 15, and the lowest (2.5 MPa) was found in LMU 2. For Inceptisols, the highest average CI (10.50 MPa) was observed in LMU 5, and the lowest (3.17 MPa) was in LMU 9. The average CI for Andisols is 4.46 MPa, while Inceptisols is 7.00 MPa. Despite the varying results, both soil types fall in the high class, showing susceptibility to excessive soil density. Medium soil density is advantageous for agricultural land preparation, while high-density soil can restrict permeability and respiration (Pang et al., 2013). Andisols, characterized by a crumbly to very crumbly structure and high levels of organic matter and water absorption, generally have a lower soil density than Inceptisols (Yatno et al., 2016).

Table 5
Effect of soil type and slope on soil cone index (CI)

Land characteristics	p-value
Soil type	0.000**
Slope	0.000**

Remark: **) = significant at 1% level of test

3.4. The Distribution of CI in Various Slopes

The Fig. 10 shows that slope class 0–8% CI significantly differs from 8–15%, 15–25%, 25–45%, and >45%. Slope class of 0–8% provides significantly higher CI results with an average

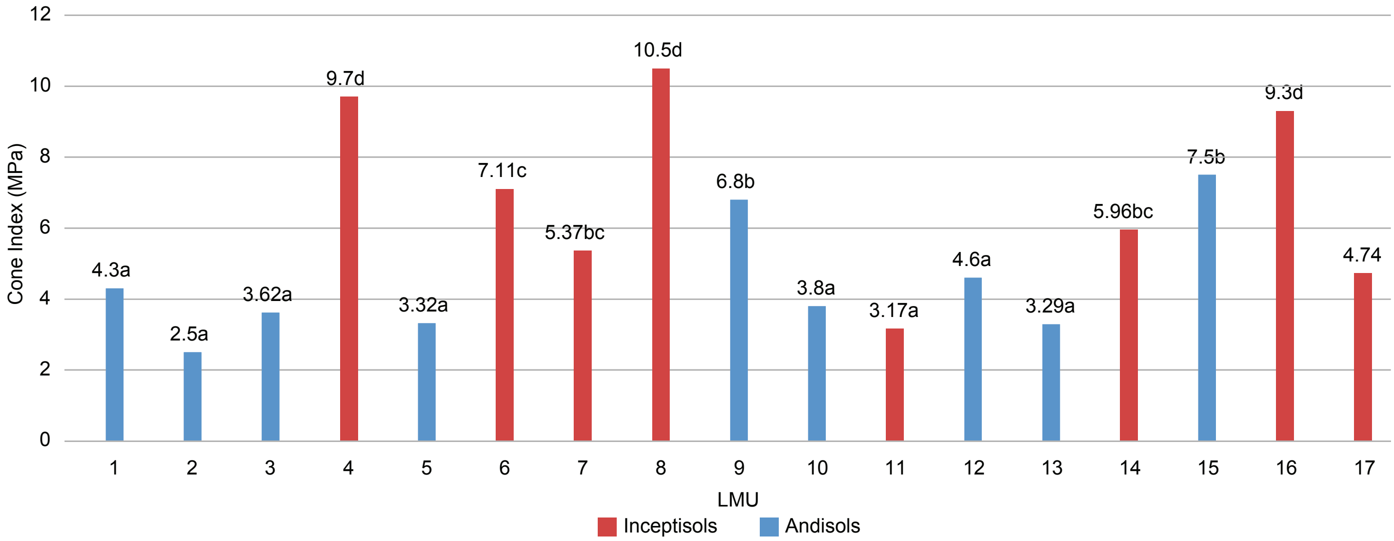

Fig. 9. The distribution of soil CI in Andisols and Inceptisols
Remark: The same notation letter indicates no significant difference in the DMRT at the 5% level.

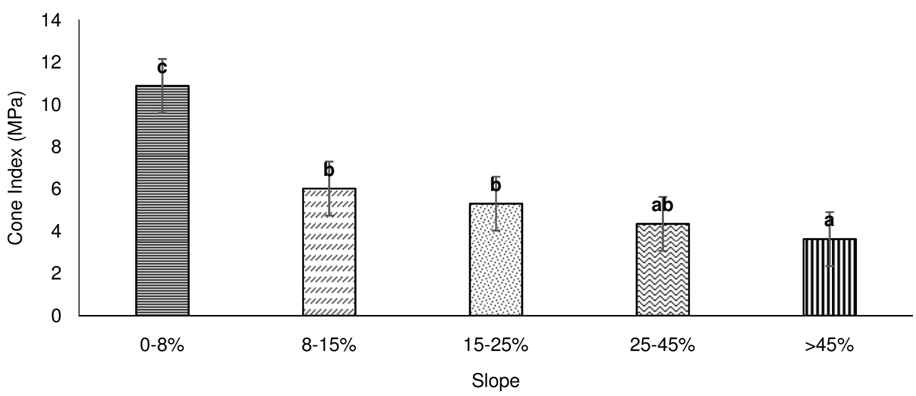

Fig. 10. The distribution of soil CI under various slope of the research area
Remark: Numbers followed by the same letter notation indicate no significant difference in Duncan's Test at the 5% level.

value of 10.88 MPa. A slope of >45% has the lowest average CI value of 3.62 MPa, suggesting that a greater slope correlates with higher water storage capacity. Huang et al. (2013) showed that the differences between slope classes had significant variation in increasing water storage capacity. On a slope of 8–15%, it is 6.02 MPa. On a slope of 15–25%, it is 5.30 MPa; on a 25–45%, the average CI is 4.34 MPa. Based on DMRT analysis, CI value will increase as slope decreases. An increase in slope can also have a corresponding effect on erosion occurrence (Elvina and Utami, 2024). Similarly, Arvin et al. (2012) identified the negative correlation in some LMU, as shown by CI value with slope. Areas with higher slope suggested lower CI value and vice versa. An increase in slope can also have a corresponding effect on the occurrence of erosion.

3.5. Determinant Factor of CI

A determinant factor of CI is based on the relationship test using Pearson's Correlation, as shown in Table 6. Based on the results, bulk density has a highly significant positive correlation with CI and texture. In comparison, moisture content and organic-c content have a significant negative correlation.

The Pearson's correlation analysis results in Table 6 show that CI has a highly significant positive correlation with bulk density (r = 0.358; P-value = 0.01; N = 51). This suggests that a higher CI value correlates with a greater bulk density value, indicating more soil compaction. The regression coefficient is positive based on the regression analysis results in Fig. 11. This suggests that an increase will follow any increase in CI value in bulk density. The value of the coefficient of determination (R2) is 31.69%, which means that bulk density affects 31.69% of CI.

As shown in Table 6, CI has a significant positive correlation with texture (r = 0.293; P-value = 0.037; N = 51). This suggests that more clay content will affect soil high penetration resistance, as measured by CI. Similarly, Vaz et al. (2011) reported that penetration resistance value would increase with high clay content due to soil-metal adhesion forces. The high clay content makes the moisture content value higher when compared to sandy soil (Baio et al., 2017). Based on the regression analysis, Fig. 12 shows a positive correlation, and the value of R2 is 11.44%, meaning texture affects CI by 11.44%.

Moisture content and CI have a significant negative correlation (r = –0.300; p-value = 0.032; N = 51). Soil with low moisture content has a low water-holding capacity, increasing susceptibility to compaction. This indicates that higher moisture content leads to a lower CI value. Kumar et al. (2012) also reported that a decrease would follow an increase in CI value in moisture content. Decreased moisture content can improve the estimation of bulk density values using CI (Molina Jr. et al., 2013). The regression analysis results in Fig. 13 show a negative coefficient between moisture content and CI, with R2 value of 11.91%.

Table 6
Determinant factors of soil cone index

	Bulk density	Texture	Porosity	Organic-C	Moisture content	Cone Index
Bulk density	1					
Texture	0.081	1				
Porosity	–0.768**	0.028	1			
Organic-C	–0.511**	–0.188	0.181	1		
Moisture content	–0.660**	0.081	0.205	0.512	1	
Cone Index	0.358**	0.293*	–0.191	–0.282*	–0.300*	1

Remark: **) correlation significant at the 0.01 level; *) correlation significant at the 0.05 level

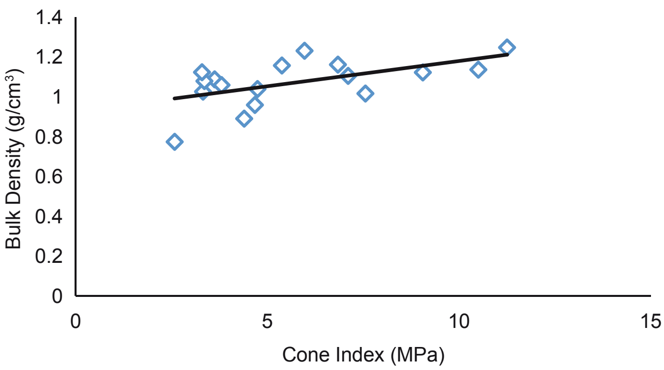

Fig. 11. Correlation of CI with bulk density

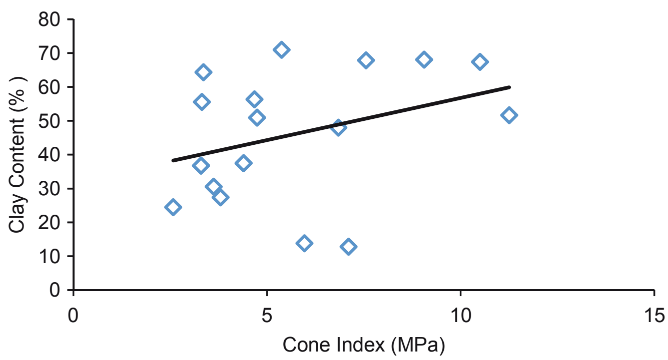

Fig. 12. Correlation of CI with clay content

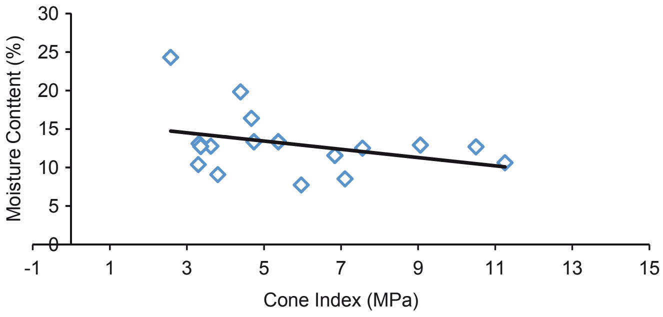

Fig. 13. Correlation of CI with moisture content

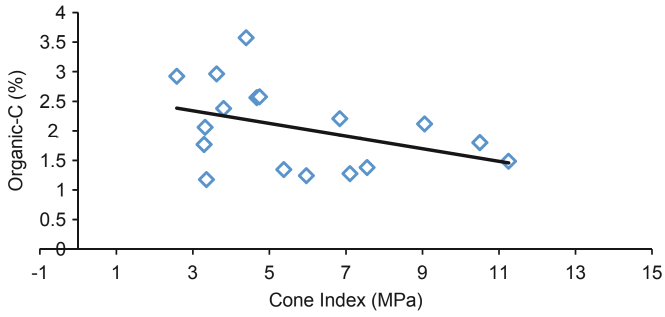

Fig. 14. Correlation of CI with organic-c

Organic-c significantly correlates negatively with CI (r= –0.346; P-value = 0.045; N= 51), as shown in Fig. 14. The R2 value or the determining coefficient is 15.75%, indicating that organic-c affects CI by 15.75%. Tian et al. (2020) stated that penetration resistance was obtained with lower values in soil profiles having higher organic-c. The reduction of organic matter is partly due to soil penetration resistance caused by compaction from ineffective agricultural processing practices (Pulido-Moncada et al., 2014a; Olivares et al., 2020).

3.6. Land management recommendations

Based on the physical and chemical properties of soil with CI, strengthened land management is essential to promote sustainable agricultural land use and contribute to better food production. Several land management recommendations that can be applied include the addition of organic materials in the form of manure, crop residue, compost, vermicast, cocopeat, biochar, and land cultivation. Organic matter also plays a role in improving water-holding capacity, thereby facilitating water entry into the pores and permeability of soil. Tillage combined with the application of organic fertilizers, such as manure and crop residue-based fertilizers, has been proven effective in improving soil quality and fertility (Sumarniasih and Antara, 2021). Additionally, tillage with the addition of manure significantly affects soil porosity and density. Cocopeat can act as an enhancer of organic matter in soil, which decreases bulk density. Organic matter with different types has potential to reduce soil bulk density. For example, in a mixture of manure with soybean crop residues and straw, organic-c is often preferred compared to other treatments.

Biochar is a solid material with carbon from biomass that has gone through pyrolysis. The results of applying biochar derived from Gliricidia sepium prunings and corn stover, as well as cow dung showed a significant effect on bulk density with an 8.59% decrease, and pore space increased by 8.90% compared to rice husk biochar. The dose of biochar applied from 3 tons/ha to 9 tons/ha affected the decrease in bulk density by 8.47% and increased soil porosity by 6.34%. The combination of biochar and compost application has also been proven to reduce bulk density of soil with clay texture. In line with the analysis, the application of compost fertilizer doses of 10 tons/ha and 40 tons/ha corn stalk biochar can reduce bulk density value by 26.5% from 1.02 g cm^{-3} to 0.75 g cm^{-3}.

4. Conclusions

In conclusion, CI in Slogohimo Subdistrict ranges from 2.58 MPa to 11.25 MPa, placing it in the high to extremely high compaction classes. The high CI class occupies the largest area at 2,116.83 ha (39.50%), followed by the extremely high at 1,918.13 ha (35.79%) and the very high class at 1,324.54 ha (24.71%). Furthermore, soil type and slope have a highly significant impact on CI, with organic carbon content, bulk density, soil texture, and moisture content identified as key determining factors. Higher levels of organic carbon and moisture content are associated with lower CI values, while elevated bulk density and clay content contribute to increased values. To optimize CI to a medium level, recommendations are made to implement land management practices that incorporate organic matter, such as manure, crop residue-based fertilizers, biochar, compost, and cocopeat, at effective application rates.

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Conflict of interest

The authors declare no conflict of interest.

Author Contributions

Mujiyo – Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Rahayu** – Supervision, Methodology, Validation, Writing – review. **Aktavia Herawati** – Supervision, Writing – review. **Riskha Safira** – Investigation, Writing – original draft. **Muhammad Rizky Romadhon** – Investigation & Collecting data, writing – review & editing. **Nanda Mei Istiqomah** – Investigation & Collecting data, writing – review & editing. **Viviana Irmawati** – Data analysis and Interpretation, Writing – review & editing. **Tiara Hardian** Data analysis and Interpretation, Visualization, Writing review & editing. **Akas Anggita** – Writing review & editing. **Khalyfah Hasanah** – Writing – review & editing. **Dwi Utari** – Visualization, Writing – review & editing.

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