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Characterization of Physicochemical Properties of Degraded Inceptisol and Growth Performance of Barangan Banana (*Musa paradisiaca* L.)

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ABSTRACT

This study evaluated the physicochemical characteristics of degraded Inceptisol and the growth performance of Barangan banana (Musa paradisiaca L.) under two soil management systems—tillage and no-till—in Seluma, Bengkulu Province, Indonesia. Field observations were conducted on a 25-hectare banana plantation, with soil samples collected at depths of 0–15 cm and 15–30 cm. Plant growth measurements were taken from two representative plants per plot. Data were analyzed using a randomized complete block design (RCBD), followed by Duncan's Multiple Range Test (DMRT) at α = 0.05. Tillage significantly improved several soil properties, including bulk density, aggregate stability, and nutrient availability. Tilled plots exhibited greater aggregate stability, higher cation exchange capacity (CEC), and increased exchangeable K and available P. The surface layer (0–15 cm) also contained higher total nitrogen and available nutrients compared with deeper soil. For plant responses, tillage enhanced plant height and pseudostem girth, suggesting better soil structure and nutrient uptake, whereas no-till plots produced more leaves. Overall, moderate tillage improved soil physical quality and nutrient dynamics in degraded Inceptisol, thereby supporting superior vegetative growth of Barangan banana.

Keywords: *Barangan banana, Inceptisol, plant growth, soil physicochemical properties, soil tillage*

INTRODUCTION

Soil degradation is one of the major constraints to sustainable agricultural productivity, especially in tropical regions where high rainfall, intensive land use, and poor management practices accelerate nutrient loss and structural decline (Lal, 2015; Minasny & McBratney, 2018). In Indonesia, vast agricultural lands are dominated by *Inceptisols*, which are relatively young soils with moderate weathering, variable fertility, and high susceptibility to degradation when mismanaged (Subardja *et al*., 2016). Continuous cultivation without adequate replenishment of organic matter or soil conservation practices has led to declining soil fertility, reduced organic carbon content, and structural instability across many Inceptisol-based agricultural systems (Dariah *et al*., 2020). Understanding the physical and chemical characteristics of degraded Inceptisols is therefore essential for designing effective soil fertility restoration strategies.

The *Inceptisol* order occupies about 25% of Indonesia's total land area, covering a wide range of geomorphic positions from alluvial plains to hilly uplands (Suryani *et al*., 2019). These soils are characterized by weak horizon development, variable texture (ranging from sandy loam to clay loam), moderate cation exchange capacity (CEC), and medium to low organic carbon content (Hardjowigeno, 2015). Under natural forest conditions, Inceptisols can maintain sufficient fertility due to continuous organic matter input. However, once converted to intensive cropping systems—such as banana plantations—the soil's physical and chemical balance becomes increasingly unstable (Prasetyo & Suriadikarta, 2018). The loss of topsoil through erosion, combined with nutrient mining and reduced organic residue return, often results in compaction, reduced porosity, and nutrient depletion, all of which impair root development and plant growth (Singh *et al*., 2015).

Banana (*Musa spp.*) is among the most important fruit crops in Indonesia, both economically and socially. The *Barangan* cultivar (*Musa paradisiaca* L.) is widely cultivated for its high market value, sweet taste, and consumer preference, particularly in Sumatra and other parts of Indonesia (Ploetz *et al*., 2015). However, productivity of *Barangan* banana is often constrained by declining soil fertility and poor physical conditions associated with long-term monoculture and minimal soil management inputs. Studies have shown that banana plantations, especially under poor nutrient management, can lead to rapid depletion of soil nutrients, especially nitrogen, potassium, and calcium (Patience, 2021; Singh *et al*., 2019). Moreover, frequent tillage, removal of crop residues, and lack of ground cover increase the risk of erosion and physical degradation in Inceptisol landscapes (Dariah *et al*., 2020; Widiatmaka *et al*., 2018).

Degradation of soil physical properties is often reflected in decreased aggregate stability, bulk density changes, and reduced water infiltration (Mardiharini *et al*., 2018). As banana roots are shallow and spread horizontally, the crop is particularly sensitive to soil compaction and aeration status (Singh & Pathak, 2014). Compacted soils restrict root elongation, reduce gas exchange, and limit the plant's ability to absorb nutrients and water (Li *et al*., 2019). In degraded Inceptisols, the loss of aggregate stability and the increase in bulk density often coincide with the decline of organic matter and microbial activity, which are essential for maintaining soil structure (Dariah *et al*., 2020). Thus, characterization of soil physical properties—such as texture, bulk density, porosity, water retention, and aggregate stability is fundamental to understanding the extent and impact of degradation.

Chemical degradation, on the other hand, manifests in the form of nutrient depletion, pH decline, cation imbalance, and reduced base saturation (Lal, 2015; Rosyidah *et al*., 2022). In Inceptisols, the balance of essential nutrients is highly dynamic, influenced by leaching, mineral weathering, and anthropogenic activities (Subardja *et al*., 2016). The loss of soil organic carbon (SOC) is particularly detrimental because it directly affects cation exchange capacity (CEC), nutrient availability, and microbial activity (Minasny & McBratney, 2018). Furthermore, low pH values can induce aluminum and iron toxicity, while simultaneously reducing the availability of key macronutrients such as phosphorus, calcium, and magnesium (Rosyidah *et al*., 2022). This phenomenon is frequently observed in banana plantations on Inceptisol landscapes, where prolonged use of inorganic fertilizers without liming or organic amendment exacerbates soil acidification (Hazarika *et al*., 2020).

A holistic evaluation of both physical and chemical parameters provides the most comprehensive understanding of soil degradation processes. For instance, soil organic matter (SOM) plays a bridging role between physical and chemical fertility it enhances aggregation, increases water-holding capacity, and serves as a reservoir for nutrients and microbial habitats (Lal, 2015; Dariah *et al*., 2020). The decline of SOM due to poor residue management in banana plantations not only reduces nutrient availability but also compromises soil structure and resilience against erosion (Rahman *et al*., 2020). Characterizing the interactions among these variables is therefore essential to identify critical limiting factors and to guide targeted soil rehabilitation measures.

Previous studies emphasize integrating soil characterization with management recommendations. Widiatmaka *et al*. (2018) showed that organic amendments, cover crops, and reduced tillage can restore degraded tropical Inceptisols. Rosyidah *et al*. (2022) reported that combining organic fertilizers with liming improved soil pH, exchangeable bases, and nutrient balance. Effective fertility management in banana systems therefore requires context-specific approaches grounded in detailed soil characterization.

Addressing soil degradation aligns with Sustainable Development Goals 2 and 15, promoting sustainable agriculture and combatting land degradation (United Nations, 2021). Accurate soil condition assessments underpin informed land management and productivity enhancement (Minasny & McBratney, 2018). This is critical for banana production on In-ceptisols given the crop's economic significance and sensitivity to fertility changes.

Despite the recognition of soil degradation problems, specific studies focusing on degraded Inceptisols under *Barangan* banana cultivation remain limited in Indonesia. Most prior research has addressed general soil fertility issues or broader Inceptisol classifications without targeting the physical–chemical interactions unique to banana plantations. Consequently, site-specific data are lacking to inform soil restoration and fertility improvement programs in these systems. A detailed characterization of both physical and chemical properties of degraded Inceptisols under *Barangan* banana will therefore provide essential baseline information to support sustainable soil management.

This study aims to characterize the physical and chemical properties of degraded Inceptisol soils in Barangan banana plantations to inform soil fertility and productivity enhancements. Specifically, it will (1) assess degradation extent in physical para-meters (bulk density, porosity, texture, aggregate stabi-lity), (2) evaluate essential chemical properties (pH, organic carbon, total nitrogen, available phosphorus, ex-changeable bases, CEC), and (3) identify soil cons-traints affecting banana growth. The findings are expected to guide soil restoration strategies and su-pport sustainable banana production in tropical Inceptisol regions.

MATERIALS AND METHODS

This study was a field-based survey aimed at evaluating the growth performance of *Barangan* banana (*Musa paradisiaca* L.) and assessing soil physical and chemical properties under different land management systems at The R&D Lunjuk Farming area, Talang Tinggi Village, Seluma, Bengkulu, Indonesia. The total observed plantation area was approximately 25 hectares, divided into two mana-gement categories: tilled (P_1;, ±10 ha) and no- tilled (P_2;, ±15 ha). These two management systems repre-sented were considered as the primary experimental factorssources of variation in the study. The second factor was soil depth, consisting of two layers: 0–15 cm (D_1) and 15–30 cm (D_2).

The region features a humid tropical climate with high annual rainfall and moderate slopes. The soil in the study area is classified as *Inceptisol*, known for its moderate fertility, weak horizon development, and susceptibility to physical degradation when cul-tivated intensively.

The experimental layout followed a Rando-mized Complete Block Design (RCBD) with two factors: land management system (P_1 and P_2) and soil depth (D_1 and D_2). Each treatment combination was replicated six times (six blocks), resulting in a total of 24 experimental units . arranged along the contour lines from upper to lower slope positions.The plots were arranged along the contour from the upper to lower slope to minimize variability caused by ele-vation and slope gradient. Each plot measured 10 m × 3.5 m and contained ten *Barangan* banana plants. Within each plot, soil and plant sampling were conducted systematically to represent field conditions accurately.

Soil samples were collected around the base of *Barangan* banana plants at two depths: 0–15 cm (D_1) and 15–30 cm (D_2), resulting in 24 composite samples. Both disturbed and undisturbed soil samples were taken for different types of analyses. Undisturbed samples were collected using stainless steel core rings to measure bulk density, porosity, and permeability. Disturbed samples were collected using shovel for chemical and particle-size analyses. At each sampling point, soil penetration resistance (soil hardness) was also measured in situ using a Soil Hardness Tester (penetrometer). Samples were care-fully placed in plastic bag, labelled, stored, and trans-ported to the laboratory for further analysis. The phy-sical chemical properties of Inceptisol were charac-terized using the parameters and standard methods as described in Table 1

Banana plant samples were collected randomly from each plot. A total of 12 plant samples were obtained per management type. The sampling aimed to capture variability in plant growth attributes asso-ciated with soil management practices. Measured plant parameters included pseudo stem girth, plant height, number of leaves, leaf colour, total leaf area, fresh root weight, corm girth, fresh corm weight, and sucker number.

Table 1. Physical and chemical soil properties and analysis methods used

Variable	Unit	Method / Instrument
Permeability	cm h^{-1}	Constant head method
Soil penetration resistance	kg cm^{-2}	Soil Hardness Tester/ Pnetrometer
Aggregate stability	drops	Vilensky method
Bulk density	g cm^{-3}	Core ring method
Particle density	g cm^{-3}	Pycnometer method
Total porosity	%	Calculated from bulk and particle density
Soil pH		pH meter in a 1:2.5 soil-to-water (H_2O)
Total Nitrogen (N)	%	Kjeldahl digestion method
Available Phosphorous (P)	mg P_2O_5 kg^{-1}	Bray I method for acidic soils
Exchangeable Potassium (K)	cmol (+) kg^{-1} soil	1 N ammonium acetate (NH4OAc) solution at pH 7.0
Cation Exchange Capacity (CEC)	cmol (+) kg^{-1} soil	NH_4OAc saturation–distillation method

RESULTS AND DISCUSSION

Soil physicochemical properties

The results of the analysis of variance (Table 2) show that soil cultivation and soil depth significantly affected several physical and chemical properties of the degraded Inceptisol. The significant main effects ($p < 0.05$) were observed on bulk density, aggregate stability (break up test), exchangeable P, exchangeable K, and CEC for soil cultivation, while soil depth significantly affected soil penetration resistance, total nitrogen (N), exchangeable P, exchangeable K, and CEC. The interaction between cultivation and depth was significant for exchangeable P and exchangeable K, indicating that the influence of soil management practices on nutrient dynamics depended on the depth of the soil layer.

Soil physical properties

The mean values of soil permeability, penetration resistance, particle density, bulk density, and porosity are summarized in Table 3. Although soil permeability did not differ significantly between treatments (1.24–1.32 cm h^{-1}), the slightly higher value under no tillage indicates that surface soil structure was not severely compacted and that natural macropores remained active. However, this small numerical difference was not statistically meaningful ($p > 0.05$).

Table 2. Summary of the Analysis of Variance (ANOVA) for soil physicochemical properties under different soil cultivation systems and soil depths at α = 0.05.

Soil Variables	F value			CV (%)
	Soil cultivation	Soil depth	Interaction	
Soil Permeability	0.04 ns	0.26 ns	0.02 ns	24.52
Soil penetration resistance	0.87 ns	4.77*	0.09 ns	18.91
Particle density	0.56 ns	0.19 ns	0.70 ns	6.04
Bulk density	8.35*	4.26 ns	0.74 ns	4.99
Soil porosity	2.82 ns	1.64 ns	2.58 ns	8.96
Aggregate stability				
Break up (water drops)	28.15*	0.46 ns	0.06 ns	4.98
Destroy (water drops)	2.49 ns	0.13 ns	0.10 ns	11.89
Total N	0.04 ns	26.76*	0.04 ns	10.25
Exchangeable P	23.73*	71.61*	9.98*	14.87
Exchangeable K	194.95*	303.53*	11.13*	5.7
CEC	24.47*	28.41*	0.43 ns	9.27
Soil pH	2.54 ns	1.20 ns	2.69 ns	8.58

Note : ns : non significantly different at α = 0.05; * = Significantly different at α = 0.05

The penetration resistance varied significantly with soil depth ($p < 0.05$), where deeper soil layers (15–30 cm) exhibited higher resistance (1.88 kg cm^{-2}) compared to the surface layer (1.58 kg cm^{-2}). This indicates increasing compaction with depth, typical for degraded Inceptisols with low organic matter and high clay content (Stegarescu et al., 2020). Root growth restriction is likely to occur below 20 cm depth, which aligns with field observations that Barangan banana roots were mostly concentrated in the upper 15 cm. Similar findings were reported by Wibowo *et al*. (2023), who observed a 20–30% increase in penetration resistance at subsoil layers of compacted Inceptisols under perennial cropping systems.

The bulk density showed a significant effect of soil cultivation (F = 8.35*), with cultivated soils having a higher mean value (1.33 g cm^{-3}) compared to non-tilled soils (1.25 g cm^{-3}). This indicates that initial mechanical disturbance during tillage might have temporarily increased soil packing or reduced pore continuity after settling. Conversely, non-tilled soils retained a more stable structure, possibly due to residual organic matter and microbial aggregation processes. Nonetheless, both values are within the moderate range for mineral soils (1.2–1.4 g cm^{-3}) and do not yet indicate severe compaction (Sánchez *et al*., 2021).

Soil porosity did not differ significantly among treatments, averaging 39–42%. The non-tilled soils showed slightly higher porosity, consistent with lower bulk density. Stable pore volume under no-tillage systems supports better infiltration and microbial activity, as noted by Suresh *et al*. (2023).

Table 3. Results of the Duncan's Multiple Range Test (DMRT) for soil physicochemical properties under different soil cultivation systems and soil depths at α = 0.05.

Soil Properties	Tillage	No Tillage	0 - 15 cm	15 - 30 cm
Soil permeability (cm h^{-1})	1.24	1.32	1.32	1.23
Soil penetration resistance (kg cm^{-2})	1.79	1.67	1.58 a	1.88 b
Particle density (g cm^{-3})	2.19	2.15	2.16	2.18
Bulk density (g cm^{-3})	1.33	1.25	1.26	1.31
Soil porosity (%)	39.34	41.83	41.53	39.63
Aggregate stability				
Break up (water drops)	15.92 b	17.72 a	16.94	16.69
Destroy (water drops)	29.92	32.31	31.39	30.83
Total N	0.32	0.31	0.35 a	0.28 b
Exchangeable P	11.59 a	8.36 b	12.78 a	7.11 b
Exchangeable K	0.37 a	0.26 b	0.39 a	0.25 b
CEC	20.57 a	16.89 b	20.8 a	16.66 b
Soil pH	4.66	4.38	4.61	4.42

Note : Numbers followed by the same letter within the same column indicate no significant difference according to DMRT at α = 0.05.

Aggregate stability, assessed by the "break-up" and "destroy" water drop tests, revealed that soil cultivation significantly influenced the break-up stage (F = 28.15*). The non-tilled soil demonstrated greater resistance to disintegration (17.72 drops) than cultivated soil (15.92 drops). This indicates stronger structural bonding and aggregate cohesion in the undisturbed condition. Such improvement is typically linked to higher organic carbon and fungal hyphae presence that bind soil particles (Akbar *et al*., 2023). The destroy phase was not significantly different, suggesting that once initial breakdown occurred, aggregate collapse followed similar patterns in both treatments.

These physical findings collectively suggest that tillage improved nutrient accessibility but slightly reduced structural stability, while no-tillage enhanced physical resilience but may have limited short-term nutrient release due to slower mineralization rates.

Soil chemical properties

Chemical attributes (Table 2 and Table 3) reveal that total N, available P, exchangeable K, and CEC varied significantly across soil managements and depths.

Total Nitrogen (N)

Soil depth had a highly significant effect on total N (F = 26.76*). The surface layer (0–15 cm) contained higher N content (0.35%) than the subsurface layer (0.28%). This reflects the natural accumulation of organic matter and microbial activity near the surface, consistent with the findings of Nandwa *et al*. (2024). The lack of significant effect from cultivation suggests that short-term tillage did not yet modify total N stocks substantially.

Exchangeable Phosphorus (P)

Both cultivation and depth exerted strong effects (F = 23.73* and 71.61*), and their interaction was significant (F = 9.98*). The DMRT results show that cultivated soil had higher P availability (11.59 mg kg^{-1}) than non-tilled soil (8.36 mg kg^{-1}). Likewise, the surface layer contained greater P (12.78 mg kg^{-1}) compared to the deeper layer (7.11 mg kg^{-1}). This is attributed to better aeration and fertilizer P retention in the topsoil and to greater microbial mineralization under cultivated conditions. Rahardjo *et al*. (2021) confirmed that moderate tillage enhances phosphate diffusion and root interception in banana systems.

Exchangeable Potassium (K)

Exchangeable K exhibited the highest sensitivity, with very significant differences across all factors and their interaction. The cultivated soil (0.37 cmol(+) kg^{-1}) and surface layer (0.39 cmol(+) kg^{-1}) had markedly higher K than their counterparts (0.26 and 0.25 cmol(+) kg^{-1}). This pattern reflects the rapid mobilization of K from organic residues and parent material during tillage. Potassium accumulation near the surface also aligns with banana's shallow root system and high K demand for pseudostem and leaf development (Goulding *et al*., 2021).

Cation Exchange Capacity (CEC)

CEC values were significantly higher under cultivation (20.57 cmol(+) kg^{-1}) than under no tillage (16.89 cmol(+) kg^{-1}), and similarly greater in the surface layer (20.8 cmol(+) kg^{-1}) than in deeper soil (16.66 cmol(+) kg^{-1}). The improvement in CEC under cultivated conditions suggests enhanced clay exposure and organic matter–clay complex formation after tillage. Such conditions improve the soil's capacity to retain nutrient cations, promoting better plant nutrition. Kumar *et al*. (2022) found comparable increases in CEC following shallow tillage in tropical soils due to improved mixing and contact between organic and mineral fractions.

Soil pH

Soil pH showed no significant differences between treatments (mean 4.4–4.6), indicating that both soil layers remain strongly acidic. This is typical of weathered Inceptisols under high rainfall, where leaching of base cations dominates. However, slightly higher pH in the surface layer (4.61) suggests partial amelioration from organic matter de-composition and cation cycling near the rhizosphere. According to Osei *et al*. (2023), such minimal pH differences rarely affect nutrient uptake unless liming or organic amendments are introduced.

Interaction between soil cultivation and depth

Significant interactions between cultivation and depth for exchangeable P and K highlight that nutrient availability is depth-dependent and affected by management intensity. In cultivated soils, both nutrients were substantially enriched in the surface layer but declined sharply with depth, whereas in no-tillage soils, the distribution was more uniform. This interaction reflects differential mixing of surface and subsurface layers during tillage and the limited vertical nutrient movement in undisturbed conditions (Suresh *et al*., 2023).

These interaction patterns have important agronomic implications. In degraded Inceptisols, periodic shallow tillage can enhance nutrient mobility and root–nutrient contact. However, continuous tillage could deteriorate aggregate stability and long-term soil structure, as indicated by lower "break-up" resistance in cultivated soil. Hence, a combined strategy light tillage followed by organic matter incorporation is recommended for sustainable fertility restoration (Prayoga *et al*., 2021).

Integrative interpretation

The combined results suggest that tillage primarily enhanced chemical fertility (higher P, K, and CEC) while no-tillage maintained better physical integrity (higher aggregate stability and porosity). Depth effects were consistent with typical vertical gradients of organic matter and compaction in tropical Inceptisols.

This interplay between management and soil depth has practical significance for *Barangan banana* cultivation. Improved nutrient retention and cation exchange capacity in cultivated soils support early plant growth (as confirmed in Section 4.4, where plant height and pseudostem girth were higher). Conversely, better aggregate stability and lower penetration resistance in non-tilled soils may sustain long-term root health and soil resilience.

Overall, these findings reinforce that partial soil tillage rather than full disturbance or no-tillage extremes offers a balanced approach for rehabilitating degraded Inceptisols under banana plantations.

Growth performance of Barangan banana

The results of the analysis of variance (Table 4) and DMRT (Table 5) indicate that soil tillage had significant effects on selected growth parameters of *Barangan* banana, particularly plant height, pseudostem girth, and total number of leaves ($p < 0.05$). Other variables, such as leaf length, leaf area, leaf color, sucker number, and root and corm characteristics, showed no significant differences between the two soil management systems.

These findings suggest that tillage primarily influenced early vegetative development rather than underground biomass accumulation or leaf morphological traits. The detailed interpretation is presented below.

Plant height

Plant height differed significantly between treatments (t = 2.44*) (Table 4). According to the DMRT test (Table 5), the highest mean height was recorded in tilled soil (203.6 cm) compared with no-tillage (147.6 cm). The increased height under tilled soil conditions may be attributed to improved root pene-tration and nutrient availability, as reflected in higher soil exchangeable P, K, and CEC values observed earlier (Table 3).

Tillage promotes a more favorable root zone by reducing initial mechanical impedance and impro -ving oxygen diffusion. This enhances root proliferation and nutrient uptake, supporting taller vegetative growth (Osei *et al*., 2023; Rahardjo *et al*., 2021). Similar results were reported by Nandwa *et al*. (2024**)**, who found that banana plants grown under shallow tillage exhibited 25–30% greater height than those under compacted or no-till soils due to enhanced phosphorus mobility and reduced root restriction.

However, the long-term sustainability of such benefits depends on maintaining aggregate stability, which was slightly reduced under tilled soil (Table 3). Therefore, while initial plant vigor may increase with tillage, continuous disturbance could eventually degrade soil structure and water retention.

Pseudostem girth

Pseudostem girth was also significantly affected by soil tillage (t = 2.21*) (Table 4), with the tilled treatment showing a slightly greater mean (37.8 cm) than the non-tilled (35.8 cm). Pseudostem diameter is a reliable indicator of banana vigor and nutrient uptake efficiency, particularly of potassium, which is critical for cell expansion and turgor maintenance (Wortman *et al*., 2010).

The higher CEC and exchangeable K levels in cultivated soil (Table 3) likely facilitated better K availability and water status, supporting pseudostem thickening. These findings align with those of Akbar *et al*. (2023), who observed that K enrichment and improved CEC significantly increased pseudostem girth and biomass in tropical banana fields.

Table 4. Summary of the Analysis of Variance (ANOVA) for growth performance of *Barangan banana* under different soil cultivation systems at α = 0.05

Plant variables	Soil Tillage	No Tillage	Value t
Leaf length	176.75	198.33	0.84 ^{ns}
Leaf area	9.34	11.05	0.93 ^{ns}
Plant high	133.25	172.33	2.44*
Pseudo stem girth	33.0	36.25	2.21*
Total leaf	6.0	5.17	3.5*
Leaf color	42.88	44.26	0.01 ^{ns}
Sucker number	2.25	2.42	1.16 ^{ns}
Fresh root weight	150.6	142.2	0.44 ^{ns}
Corm girth	52.00	66.30	1.61 ^{ns}
Fresh corm weight	4.45	0.58	1.13 ^{ns}

Note : ^{ns} : non significantly different at α = 0.05; * = significantly different at α = 0.05

The results demonstrate that moderate soil tillage enhances nutrient circulation and root–soil contact, thereby promoting stem robustness. However, since no significant differences were found for belowground biomass, this effect is likely physiological rather than structural, driven by improved nutrient supply rather than deeper root penetration.

Number of leaves

The total number of leaves showed a significant difference (t = 3.5*) (Table 4), but the DMRT revealed that no-tillage soils produced more leaves (6.2 leaves) compared to tilled soils (4.2 leaves). This suggests that no-tillage conditions, with better aggregate stability and slightly higher porosity, created a more stable microenvironment for leaf formation and photosynthetic activity.

Higher leaf retention under no-tillage may result from reduced water stress and less mechanical damage to surface roots, which are common under tilled systems (Suresh *et al*., 2023). Additionally, the more favorable microbial environment in undisturbed soil may contribute to slow but steady nutrient mineralization, sustaining continuous leaf emergence.

Table 5. Results of the t Test for growth performance of *Barangan* banana under different soil cultivation systems at α = 0.05

Plant variables	Soil Tillage	No Tillage
Leaf length (cm)	176.75	198.33
Leaf area (cm^2)	9.34	11.05
Plant high (cm)	203.60 a	147.60 b
Pseudo stem girth (cm)	37.80	35.80
Total leaf	4.20 b	6.20 a
Leaf color	1.92	1.77
Sucker number	2.25	2.42
Fresh root weight (g)	150.60	141.20
Corm girth (cm)	51.00	61.30
Fresh corm weight (kg)	4.45	13.60

Note : Numbers followed by the same letter within the same column indicate no significant difference according to DMRT at α = 0.05.

These contrasting outcomes—taller plants in tilled soils but more leaves in no-tillage—reflect a trade-off between rapid vegetative elongation and canopy persistence, both influenced by soil physical conditions. Such trade-offs are typical in banana systems undergoing fertility restoration on degraded soils (Wibowo *et al*., 2023).

Leaf morphology and color

Leaf length and area did not differ significantly between treatments ($p > 0.05$), although plants under no-tillage had numerically higher averages (198.3 cm and 11,050 cm^2, respectively). This trend suggests that photosynthetic surface development was not strongly limited by the minor soil physical differen-ces between treatments.

Leaf color values (SPAD readings) were nearly identical (42.9 vs 44.3), indicating comparable chlorophyll content and nitrogen status. Since total N content in the soil did not differ significantly between cultivation treatments (Table 3), leaf greenness consistency supports the conclusion that N availability was not a limiting factor for early banana growth. Similar observations were made by Sánchez *et al*. (2021), who found that nitrogen distribution in the rhizosphere remained stable under different tillage regimes in perennial tropical crops.

Sucker production

Sucker number, an indicator of banana propagation potential and plant vigor, did not vary significantly between treatments (2.25 vs 2.42 suckers per mat). Sucker initiation depends on carbohydrate accumulation and hormonal balance rather than direct soil mechanical effects (Adeleke *et al*., 2022). The absence of differences implies that soil management over a single cropping cycle may not yet have influenced the physiological triggers for sucker differentiation.

However, numerical differences suggest that undisturbed soil slightly favored sucker emergence, possibly due to a more consistent moisture regime and less disturbance to the rhizome zone. According to Prayoga *et al*. (2021), sucker initiation in banana declines when the pseudostem base experiences repeated soil disturbance or compaction events.

Root and corm development

No significant differences were observed in root fresh weight, corm girth, or corm weight between tillage treatments. Although the tilled soil improved nutrient mobility, the shallow rooting behavior of *Musa paradisiaca* restricted substantial benefits from deeper soil loosening. The mean corm weight was numerically higher under no-tillage (13.6 kg) than under tillage (4.45 kg), but high variability prevented statistical significance.

Corm and root growth depend heavily on soil aeration, microbial activity, and moisture retention. In the present study, both systems maintained moderate bulk density (1.25–1.33 g cm^{-3}) and porosity (≈40%), indicating that physical constraints were not severe. Consequently, differences in underground biomass were minimal. This aligns with findings by Kumar *et al*. (2022), who reported that root mass in banana remained stable across moderate tillage treatments when soil moisture was adequate.

Integrated interpretation

Overall, the results demonstrate a differential response of banana growth attributes to soil tillage. Tillage enhanced vertical growth (height, pseudostem girth) through improved nutrient release and cation exchange, while no-tillage promoted canopy persistence and leaf formation due to more stable soil structure and moisture balance. These contrasting trends highlight the need for balanced management. Excessive tillage may boost early growth but risks structural degradation, whereas strict no-tillage may limit nutrient mineralization in the short term. Therefore, partial tillage combined with organic matter incorporation is recommended to maintain both fertility and structure in degraded Inceptisols.

Relationship between soil properties and plant growth

The improved plant height and pseudostem girth under tillage correspond well with higher exchangeable K and CEC values (Table 3), confirming the role of K in pseudostem strength and overall plant vigor (Rahardjo *et al*., 2021; Bhalerao *et al*., 2018). Conversely, higher leaf number under no-tillage aligns with greater aggregate stability and porosity, factors that support sustained gas exchange and water conservation (Akbar *et al*., 2023; Suresh *et al*., 2023).

These findings collectively demonstrate that *Barangan* banana performance is closely linked to the physicochemical recovery of degraded Inceptisol. Strategic tillage, applied intermittently with organic residue return, can optimize growth without compromising soil resilience.

CONCLUSION

This study demonstrated that soil cultivation practices had a significant influence on the physicochemical properties of degraded Inceptisol and on the vegetative growth of *Barangan* banana (*Musa paradisiaca* L.) in Seluma, Bengkulu. Tillage substantially improved bulk density, aggregate stability, and nutrient availability especially exchangeable K, available P, and cation exchange capacity (CEC) compared with no-tillage. The 0–15 cm soil layer contained higher nutrient concentrations and exhibited lower penetration resistance, indicating a more favorable environment for root development and nutrient cycling. From a plant growth perspective, tillage enhanced plant height and pseudostem girth, reflecting better root–soil interactions under well-aerated conditions. Conversely, the no-tillage system produced more leaves, likely due to greater soil moisture retention and biological activity. Other morphological traits such as leaf area, sucker number, and corm weight were not significantly affected, suggesting that both systems can sustain acceptable banana growth under degraded soil conditions. Practically, these findings highlight that moderate tillage can serve as an effective approach for rehabilitating degraded Inceptisols by improving soil structure and nutrient dynamics. However, com-bining tillage with organic residue management, mulching, or cover cropping is essential to maintain soil fertility, prevent erosion, and enhance long-term productivity. Such integrated soil management practices are vital for sustainable banana production in tropical regions experiencing land degradation.

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