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Impacts of oil palm cultivation on spatial variations in soil properties in an oil palm cultivated land in Kalutara, Sri Lanka

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ABSTRACT

In Sri Lanka, the impacts of oil palm (*Elaeis guineensis*) cultivation on soil properties remain insufficiently examined, especially regarding spatial variations within a single plantation. This study examined the spatial variations of physical and chemical soil properties under oil palm cultivation at Culloden Estate in Kalutara, Sri Lanka, from June to December 2024. The objectives of this study were to evaluate the impact of oil palm cultivation on soil properties and to assess the spatial variability between cultivated sites and a reference site. The plantation was divided into three sites, each with three representative sampling points. The reference site was selected from an adjacent grassland. Selected soil properties were analyzed using standard laboratory methods. Significant spatial differences in all assessed soil properties were observed relative to the reference site ($p<0.05$, Generalized Linear Model). The reference site showed higher pH, electrical conductivity, porosity, organic matter, and nitrogen levels, whereas cultivated sites reported higher bulk and particle densities, cation exchange capacity, and phosphorus content. While physicochemical parameters varied significantly within the plantation, no directional pattern was identified. The cluster analysis reported three sub-clusters. Sites 2 and 3 formed one cluster, while Sites 1 and the reference site formed separate groups, indicating variations in land-use practices. Higher soil bulk density indicated soil compaction under oil palm. Although soil properties differed from the reference site, they remained within acceptable global ranges for oil palm cultivation, indicating no major soil degradation. This study highlights the need for broader, multi-site research to support sustainable soil management.

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1. INTRODUCTION

Soil degradation has emerged as a major concern in most oil palm cultivation areas, where soil erosion (Guillaume et al., 2015) and soil compaction (Kotowska et al., 2015) contribute considerably to the problem. Analyzing soil parameters in croplands is important for understanding soil health and fertility, which directly affects crop yield and quality. Soil properties are generally continuous variables that vary with direction and distance relative to nearby sampling points (Ditzler, 2017). The soil's physical condition directly and indirectly affects the production of crops and environmental quality, both of which depend on crucial soil parameters (Shah & Wu, 2019).

Various soil parameters are measured and analyzed to make informed decisions regarding crop management. Once the data on the variability of these parameters are collected, they can be used to make informed decisions about soil spatial changes, crop selection, fertilization, irrigation, and other management practices. Therefore, regular soil monitoring and appropriate adjustments are important to maintain soil fertility along with long-term productivity. Long-term soil parameter data are crucial for evaluating the sustainability of specific land uses (Boafo et al., 2020).

One of the earliest investigations of long-term soil changes under oil palm cultivation was carried out by Tinker

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in 1963 in West Africa. The study reported a notable increase in soil fertility during the initial five years. However, subsequent reductions were recorded in potassium, magnesium, and pH levels, while soil organic carbon remained stable (Tinker & Smilde, 1963). Several studies have reported that nitrogen, phosphorus, potassium, and magnesium are the key soil nutrients required by oil palm for adequate vegetative growth and optimal fresh fruit bunch (FFB) yield (Joseph et al., 2017).

Soil acidification is also a major problem in oil palm cultivation. Research conducted in Papua New Guinea's high rainfall areas indicated that in permeable soils, the topsoil experienced a pH drop of 0.52 to 0.96 over four years due to nitrate leaching caused by ammonium-based fertilizer application (Hambloch, 2022). Organic matter content and efficient application of nitrogenous fertilizers help alleviate soil acidification in oil palms. Physical properties of soil, including soil depth, texture, and structure, are key properties that determine the suitability of large-scale oil palm planting (Rozieta et al., 2015). Apart from changes in soil properties, it was also reported that soils are characterized by a high degree of spatial variability due to the combined effects of physical, chemical, or biological processes that operate with different intensities and scales (Delgado & Gómez, 2016).

Spatial variations in soil properties can result from natural heterogeneity in soil properties as well as from anthropogenic activities. Previous studies on soil variability reported high variation between soil properties of two closely spaced locations, 10 m apart, in a uniform terrain (Piotrowska-Długosz et al., 2016). Variability occurs because of the type of land use and management. Soil acidity and nutrient depletion are two major constraints in oil palm cultivation in the tropical region (Mahmud & Chong, 2022). Most of the time, the reasons for these changes are improperly managed fertilizer applications. A high quantity of fertilizer application indicates that oil palms were either under-fertilized or over-fertilized (Behera et al., 2016). Soil moisture content also has a significant impact on soil quality in oil palm cultivation (Suwardi et al., 2022). For these reasons, quantifying the variability of soil properties in oil palm plantations is very important. Soil properties and their ranges at various points generally fluctuate according to changes in direction and distance from nearby samples. Therefore, to locate homogeneous areas, it has been recognized that the spatial characterization of soil properties is important to carefully manage agriculture towards sustainable development (Mahmud & Chong, 2022). Since oil palm cultivation is implemented on a large scale, it generally exhibits high spatial variations within the plantation. Therefore, the characterization of soil parameters is essential for comprehensive analysis and effective land management in extensive cultivations.

Oil palm has been extensively cultivated in Malaysia, Indonesia, Thailand, Benin, Cameroon, Colombia, Ecuador, and India. Oil palm cultivation became a controversial topic in Sri Lanka in recent years, highlighting environmental degradation as one of the main points of discussion (Kularathna et al., 2024). Several research studies have been conducted to evaluate both positive and negative impacts on soil under oil palm cultivation in Sri Lanka. Research conducted in the Nakiyadeniya oil palm estate in the Galle District concluded that there is a substantial impact of oil palm cultivation on the soil, groundwater table, and well water depth (Dissanayaka & Bandara, 2020). However, it could not be concluded confidently that oil palm cultivation has a serious impact on soil compared with other crop types. Researchers at the Wayamba University of Sri Lanka conducted research and reported that soil moisture content and the soil nitrogen content in 15- and 5-year-old oil palm plantations were higher compared with rubber plantations of the same age (Liyanagama et al., 2016).

Although several studies have analyzed the effects of oil palm cultivation on soil properties in tropical regions, their findings have often lacked sufficient depth, especially regarding the degree and direction of changes in soil physical and chemical characteristics. Moreover, in the context of Sri Lanka, the spatial variability of soil properties within oil palm plantations remains largely underexplored, and existing findings are often contradictory. This indicates a significant research gap in understanding how oil palm cultivation affects soil health at a local scale. To address this, the present study focuses on the Culloden Estate in Kalutara as a representative site to analyze spatial variations in selected soil properties under oil palm cultivation. The novelty of this study lies in its site-specific spatial analysis within a Sri Lankan oil palm plantation, an area where such detailed analysis is currently lacking. This is particularly important for improving the understanding of the impacts of oil palm cultivation on soil health in Sri Lanka, providing site-specific, evidence-based information that may support future awareness and decision-making among farmers and stakeholders. The objectives of this study are to evaluate the impact of oil palm cultivation on selected soil properties and to analyze spatial variability between cultivated sites and a reference site.

2. MATERIAL AND METHODS

2.1. Study area

The selected study area is located in Neboda (approximately 690 hectares), Kalutara District in Sri Lanka, and spans coordinates from 6°33'00.0"N, 80°07'48.0"E (NW) to 6°30'36.0"N, 80°10'12.0"E (SE), as shown in Figure 1. The annual average temperature in the Kalutara District is 28.06 °C. The mean relative humidity level is around 88%. Neboda typically receives an average monthly precipitation of 320 mm and has approximately 270.2 rainy days (74% of the time) annually. The agroecological zone is identified as the Low Country Wet Zone (Agroecological Zone Classification: WL1b). According to the soil map of Sri Lanka, the Neboda area contains Red-Yellow Podzolic soil. The selected oil palm land for the study is approximately 21 hectares in area and was cultivated in 2001. and it belongs to the Culloden estate of Agalawatta Plantations. The land lay uncultivated before the growth of the oil palm. The selected reference site is a small grassland, which can be considered abandoned land, that has been undisturbed for nearly 20 years, with no human impact on the soil properties, and it is located 400 m away from the oil palm cultivated land.

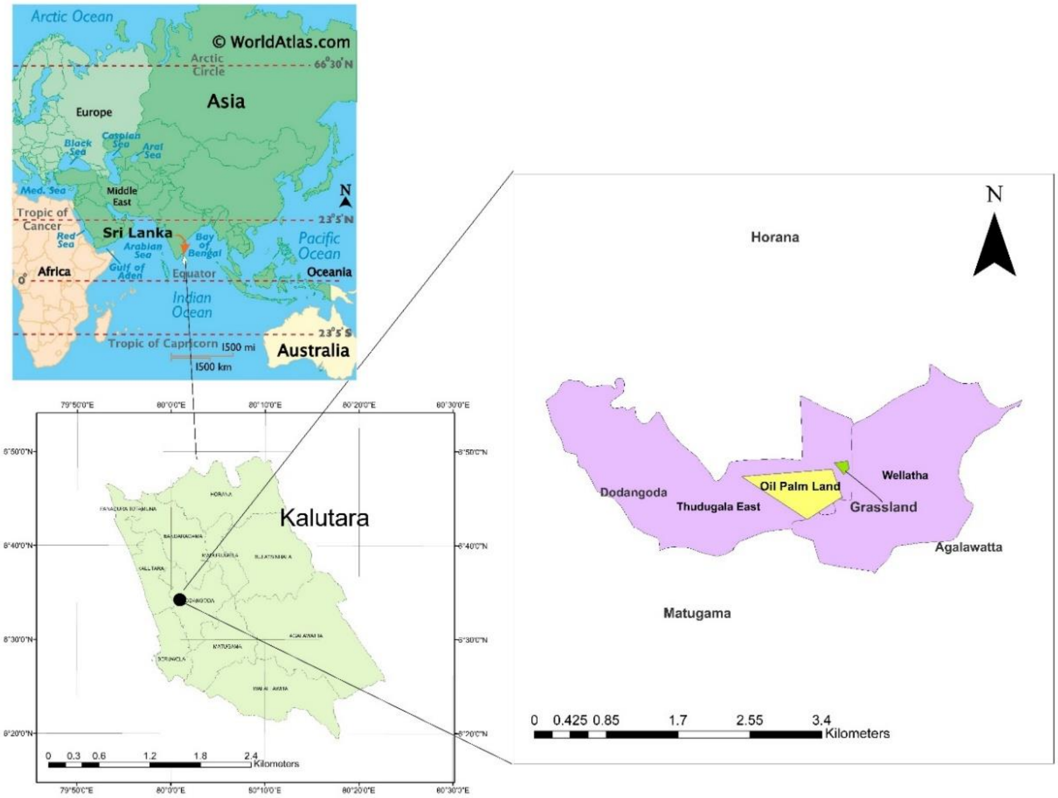

Figure 1. Map of the study area showing the locations of the oil palm cultivation sites and the reference site. (Panel 1: Location of Sri Lanka on the world map; Panel 2: Map of the Kalutara District; Panel 3: Detailed map of the study area indicating the oil palm sites and the reference site)

2.2. Sampling

Nine sampling points were selected within the oil palm plantation. The total study area was divided into three zones of approximately equal size to account for spatial heterogeneity, following a stratified sampling design. Within each zone, three representative sampling points were selected using systematic random sampling, with three replicates collected at each point. The points were spaced approximately 200 m apart across each study site. A representative sample was then prepared by mixing soil from the three sampling points within each zone. The representative samples from Site 1, Site 2, and Site 3 were designated as S1, S2, and S3, respectively. For comparison, reference samples (indicated as R) were collected from three points randomly selected within the grassland. Soil sampling was conducted using a stainless-steel hand-held screw auger (Fig. 2) at two depths of 0–30 cm (topsoil) and 30–60 cm (subsoil), sequentially over a six-month period (June to December 2024). These depths were chosen based on the known root concentration zone of oil palm, which typically extends up to 60 cm in the soil profile.

2.3. Analysis of soil parameters

The selected soil properties were analyzed using standard analytical methods at the laboratory of the University of Kelaniya, Sri Lanka. Soil pH was measured using a portable pH meter (model HI99121) (USEPA, 2016), while electrical conductivity (EC) was determined with a multi-parameter meter (model HQ40d) (USEPA, 1982). Soil texture was analyzed using the pipette method (USEPA, 2001). Bulk density was obtained through the core sampling method (Al-Shammary et al., 2018), and particle density was measured using the pycnometer method (ISO, 2017), with soil porosity subsequently calculated as indicated in Equation 1.

$$\textbf{Soil Porosity}\ (\%) = \left[1 - \left(\frac{\text{Bulk Density}}{\text{Particle Density}}\right)\right] \times 100\ \% .....[1]$$

Organic matter content was determined using the loss-on-ignition method (USEPA, 2024). Cation exchange capacity (CEC) was analysed using the ammonium acetate method (USEPA, 2015). Total nitrogen (N) was measured by the Kjeldahl method (Quirino et al., 2023), and available phosphorus (P) was determined using the modified Truog method (Shuai, 2018) (Fig. 2).

2.4. Statistical analysis

The mean ± SEM (standard error of the mean) of the replicates was obtained in descriptive statistics using IBM SPSS Statistics software (version 26) for the soil parameters that were measured during the six months. The Generalized Linear Model (GLM), followed by Tukey's pairwise comparison at the 95% confidence level, was used to determine the spatial variation of the studied soil parameters. The resemblance matrix was generated using Euclidean distance analysis in PRIMER 7 software. A cluster analysis was generated to analyze the cluster variation of soil parameters. The Analysis of Similarities (ANOSIM) was used to assess the significance of cluster variations in the study sites. The distance-based redundancy analysis (dbRDA) was used to analyze the overall influence of the studied soil parameters across four sites.

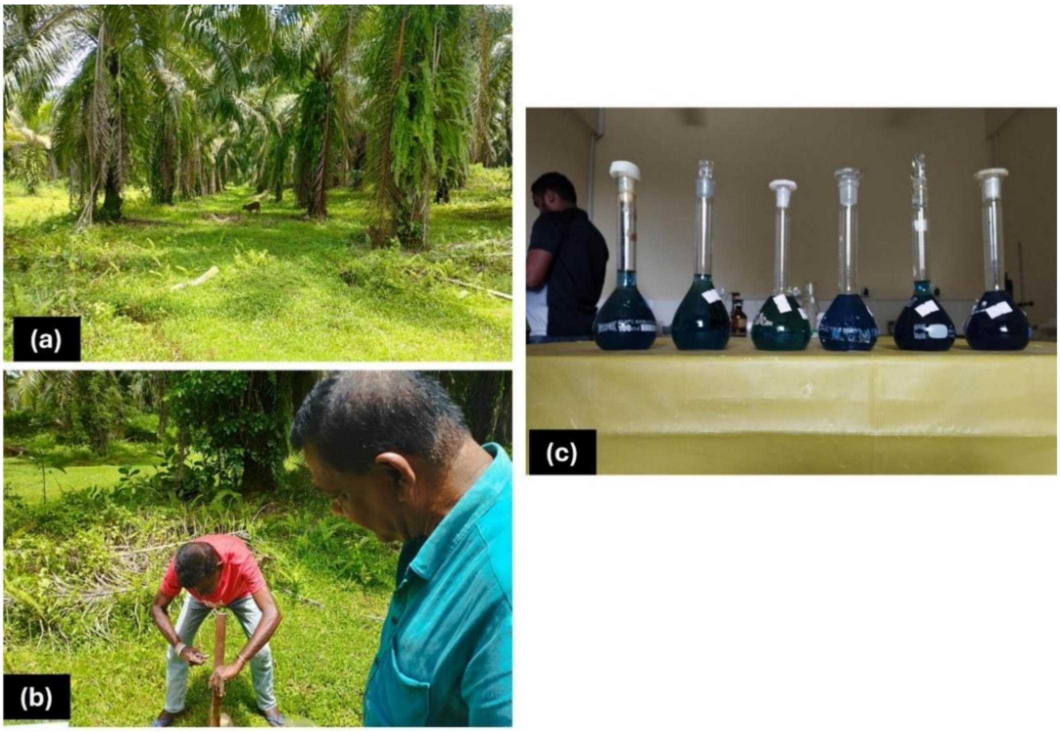

Figure 2. Soil sampling and laboratory works - (a) Oil palm cultivated site in Culloden Estate, (b) Soil sampling in the field, (c) Analysing soil phosphorus using the spectrophotometer at the laboratory

Table 1. Percentage (%) differences in soil properties of oil palm sites relative to the reference site at 30 cm and 60 cm depths

Property	30 cm depth			60 cm depth		
	S1 (% vs R)	S2 (% vs R)	S3 (% vs R)	S1 (% vs R)	S2 (% vs R)	S3 (% vs R)
pH	-1.97	-2.16	-1.80	-2.36	-2.73	-2.91
EC (µS cm^{-1})	-26.8	-17.5	-20.4	-24.1	-22.0	-15.4
Bulk density (g cm^{-3})	+81.6	+41.8	+59.8	+86.0	+40.0	+78.0
Particle density (g cm^{-3})	-0.79	-0.79	+3.15	-0.79	-2.34	+3.13
Porosity (%)	-52.2	-26.5	-27.9	-55.5	-30.6	-47.2
CEC (meq 100 g^{-1})	+4.57	-2.26	+1.38	-0.81	+0.89	-5.48
Organic Matter (%)	-5.48	-1.37	-21.9	-23.6	-27.8	-8.33
Nitrogen (%)	-53.6	-50.0	-39.3	-52.2	-47.8	-39.1
Phosphorus (ppm)	-7.85	-0.56	+6.6	-43.2	-18.8	+4.22

Remarks: *EC – Electrical Conductivity *CEC - Cation Exchange Capacity

3. RESULTS

3.1. Soil texture

According to the United States Department of Agriculture (USDA) soil texture classification, the oil palm site contained 14.9% sand, 41.3% silt, and 43.8% clay, and was classified as 'silty clay', which generally consists of medium particles between the sizes of sand and clay.

In comparison, the reference site had 17.3% sand, 46.6% silt, and 36.1% clay, corresponding to a 'silty clay loam' texture that is characterized by moderate amounts of fine sand, a small proportion of clay, and a higher quantity of silt particles.

3.2. Spatial variations in soil properties

The spatial distribution of soil properties provides insight into the underlying heterogeneity of the soil. The results obtained at 30 cm and 60 cm soil depths revealed significant differences among the sites, demonstrating notable spatial variability within the oil palm plantations as well as clear contrasts with the reference site.

Table 1 summarizes the percentage differences of each soil parameter in the oil palm sites relative to the reference site, emphasizing substantial spatial variability across the plantation. At both depths, pH and electrical conductivity were consistently lower in the cultivated sites compared with the reference site, while bulk density was significantly higher, particularly at Site 1, which recorded a value of +86% at 60 cm depth. Particle density exhibited only minor fluctuations, with slight increases observed at Site 3.

According to General Linear Model analysis, all analyzed soil parameters varied significantly ($p < 0.05$) among the study sites at both 30 cm and 60 cm depths. As shown in Table 2, at 30 cm, the reference site displayed the highest pH (5.58 ± 0.02), electrical conductivity (65.50 ± 1.03 µS cm^{-1}), porosity (61.4 ± 2.10%), organic matter (7.3 ± 0.21%), and nitrogen content (0.28 ± 0.02%). Bulk density was highest at Site 1 (0.89 ± 0.05 g cm^{-3}), while particle density was greatest at Site 3 (1.31 ± 0.01 g cm^{-3}). The highest cation exchange capacity was recorded at Site 3 (15.23 ± 0.04 meq 100 g^{-1}), and phosphorus content was also highest at Site 3 (13.21 ± 0.64 ppm).

Table 2. Spatial variation in soil properties at 30 cm depth

Site / Property	Site 1 (S1)	Site 2 (S2)	Site 3 (S3)	Reference Site (R)
pH	5.47±0.032^{a}	5.46±0.022^{a}	5.48±0.054^{a}	5.58± 0.024^{b}
EC (µS cm^{-1})	47.92±0.97^{a}	54.07±0.88^{b}	52.18±1.72^{c}	65.50± 1.03^{d}
Bulk density (g cm^{-3})	0.89±0.05^{d}	0.69±0.01^{b}	0.78±0.01^{c}	0.49± 0.002^{a}
Particle density (g cm^{-3})	1.26±0.09^{a}	1.26±0.03^{a}	1.31±0.01^{b}	1.27± 0.011^{a}
Soil porosity (%)	29.3±1.03^{a}	45.1±0.881^{b}	44.2±1.01^{b}	61.4±2.10^{d}
CEC (meq 100g^{-1})	15.23±0.04^{c}	14.23±0.29^{a}	14.76±0.21^{b}	14.56±0.3^{ab}
Organic matter (%)	6.9±0.661^{b}	7.2±0.230^{c}	5.7±0.271^{a}	7.3±0.202^{c}
Nitrogen (%)	0.13±0.09^{a}	0.14±0.004^{a}	0.17±0.05^{b}	0.28± 0.004^{c}
Phosphorus (ppm)	11.42±0.11^{a}	12.32±0.29^{b}	13.21±0.64^{d}	12.39±0.07^{c}

Table 3. Spatial variation in soil properties at 60 cm depth

Site / Property	Site 1 (S1)	Site 2 (S2)	Site 3 (S3)	Reference Site (R)
pH	5.37±0.022^{a}	5.35±0.016^{a}	5.34±0.046^{a}	5.50±0.02^{b}
EC (µS cm^{-1})	40.36±1.06^{a}	41.48±1.02^{b}	45.01±1.14^{c}	53.18±0.638^{d}
Bulk density (g cm^{-3})	0.93±0.01^{d}	0.70±0.03^{b}	0.89±0.037^{c}	0.50±0.02^{a}
Particle density (g cm^{-3})	1.27±0.01^{b}	1.25±0.010^{a}	1.32±0.018^{c}	1.28±0.02^{bc}
Soil porosity (%)	27.1±0.23^{a}	42.2±1.10^{b}	32.1±0.87^{c}	60.8±0.94^{d}
CEC (meq 100 g^{-1})	13.39 ±0.06^{b}	13.62±0.60^{c}	12.76±0.424^{a}	13.50±0.10^{bc}
Organic matter (%)	5.5±0.62^{b}	5.2±0.46^{a}	6.6±0.44^{c}	7.2±0.30^{d}
Nitrogen (%)	0.11±0.001^{a}	0.12±0.003^{b}	0.14±0.005^{c}	0.23±0.016^{d}
Phosphorus (ppm)	5.47±0.43^{a}	7.81±0.53^{b}	10.03±0.81^{d}	9.63±0.14^{c}

Notes: Values in Table 2 and Table 3 indicated as Mean ± Standard error of mean. Different superscript letters in each row depict statistically significant differences as suggested by the General Linear Model followed by the Tukey's pair-wise comparison as post-hoc analysis at 95% level of confidence

At a depth of 60 cm, similar trends were observed, as indicated in Table 3. The reference site maintained the highest pH (5.50 ± 0.02), electrical conductivity (53.18 ± 0.64 µS cm^{-1}), porosity (60.8 ± 0.94%), organic matter (7.2 ± 0.30%), and nitrogen (0.23 ± 0.02%) levels. Site 1 recorded the highest bulk density, whereas Site 2 reported the lowest particle density and organic matter content (5.2 ± 0.46%). Cation exchange capacity remained highest at Site 2 (13.62 ± 0.60 meq 100 g^{-1}), while soil phosphorus continued to be highest at Site 3 (10.03 ± 0.81 ppm).

Overall, soils under oil palm cultivation demonstrated higher bulk density, greater soil compaction, lower porosity, reduced organic matter content, lower nitrogen levels, and lower pH (indicating increased acidity) compared with the reference site. However, phosphorus availability was consistently higher in oil palm soil, likely reflecting fertilization practices. Soil particle density did not differ significantly among the sites, suggesting relative uniformity in this property, most likely due to similar mineral composition and soil texture across the study area. The spatial variation observed among the three oil palm sites indicates that plantation management practices and site-specific soil conditions contribute to heterogeneity in overall soil quality.

3.3. Cluster analysis

The mean separation status suggested by the post-hoc analysis of GLM was further verified by the dendrogram of the cluster analysis. As shown in Figure 3, based on the multivariate spatial variations of the soil parameters, the studied sites formed three main subclusters. Sites 2 and 3 appeared as one major cluster, while Site 1 and the reference site emerged as the other two subclusters. Sites 2 and 3 were grouped in a single cluster, reflecting the similarity in their soil properties, likely resulting from consistent management practices at these sites. In contrast, Site 1 formed a separate cluster, possibly due to greater anthropogenic influences. The reference site formed its own distinct cluster, indicating that its soil parameters differ from those of the oil palm cultivated sites. This separation probably reflects the absence of oil palm management practices and minimal anthropogenic disturbances, resulting in a soil more representative of natural conditions. This clustering status was statistically significant at a 95% confidence level, reporting a Global R-value of 0.97, indicating a good fit of data.

3.4. dbRDA analysis

The ordination plot of the distance-based redundancy analysis (dbRDA) for the soil parameters at 30 cm depth is shown in Figure 4. It was noted that the dbRDA 1 axis accounted for 95% of the total variation of the data set, while the dbRDA2 axis accounted for another 4.5% of the variability. Therefore, around 99.5% of the total variability was explained by the dbRDA axes, indicating a satisfactory level of goodness of fit for the collected data. According to the loading values of the analysis, soil porosity, electrical conductivity, and bulk density emerged as the main parameters influencing the dbRDA 1 axis, while organic matter content, bulk density, and cation exchange capacity influenced the dbRDA 2 axis. Consistent with previous results, the emergence of three subclusters was also observed in the dbRDA analysis. The distinct clustering of Site 1 likely reflects greater anthropogenic influences, whereas the reference site represents natural soil conditions unaffected by cultivation. Overall, the dbRDA further confirms that both management practices and environmental factors drive the observed spatial variability of soil parameters.

4. DISCUSSION

According to the results in this study, significant spatial variations in several soil parameters were identified among the oil palm sites. Statistical analysis further confirmed significant spatial variations within the oil palm cultivation. The cluster and dbRDA analyses grouped Site 2 and Site 3 into one major cluster, while Site 1 and the reference site formed two separate subclusters.

The grouping of Sites 2 and 3 can be attributed to the similarity in their soil properties, likely resulting from consistent management practices such as uniform fertilizer application, pruning, and frond removal, and reduced soil compaction due to minimal anthropogenic disturbances. In contrast, Site 1 exhibited distinct soil characteristics, including higher bulk density due to soil compaction and lower organic matter content, distinguishing it from the other oil palm sites. The reference site formed a distinct cluster, indicating that its soil parameters differ from those of the oil palm-cultivated sites due to the absence of management interventions and minimal human disturbance. These findings highlight how both cultivation-related practices and external anthropogenic impacts shape the spatial variability of soil properties within oil palm landscapes.

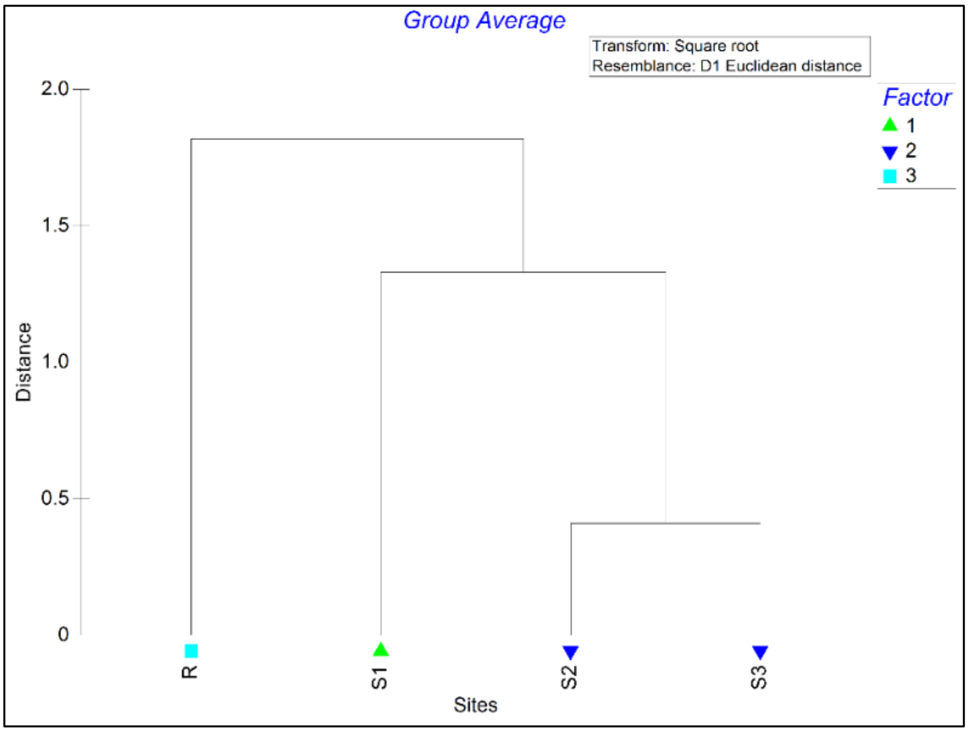

Figure 3. The dendrogram of the cluster analysis for the overall soil parameters at 30 cm depth

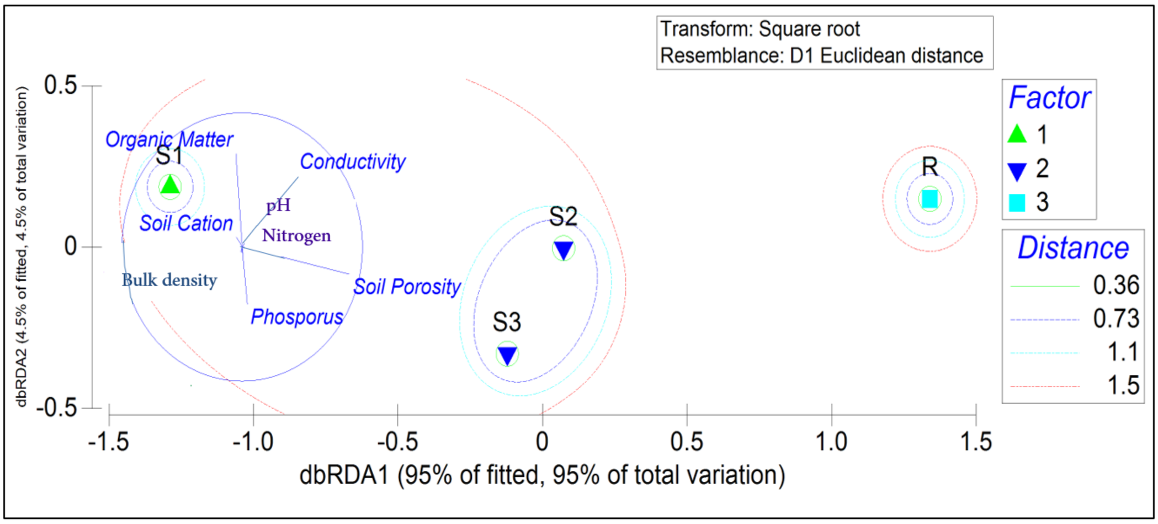

Figure 4. The ordination plot of the dbRDA analysis for soil parameters at 30 cm depth

Soil pH indicated that the oil palm soils were generally acidic; however, the values remained relatively consistent across the sites. In contrast, electrical conductivity showed notable differences, reflecting the spatial heterogeneity of soil conditions within the plantations. Bulk density also varied considerably, with Site 1 recording the highest value of 0.89 g cm^{-3}, suggesting greater soil compaction. Correspondingly, soil porosity was inversely related to bulk density, displaying similar spatial trends. Organic matter content exhibited marked variation, with Site 2 (located in the middle of the plantation) recording the highest value of 7.2 %. Meanwhile, nitrogen and phosphorus levels were strongly influenced by fertilization practices, as all sites demonstrated distinct differences, with Site 3 reporting the highest values for both parameters. Thus, although the physicochemical parameters indicated significant variation within the plantation, no consistent directional trend was observed.

Compared with the oil palm soil, the reference site exhibited notable differences in both physical and chemical properties. Soil bulk density was higher in the oil palm sites, while soil porosity was comparatively higher in the grassland. In contrast, particle density did not show a significant difference between oil palm and reference sites. Regarding chemical properties, soil pH was generally higher in the oil palm soils than in the grassland, which is consistent with the slightly acidic conditions preferred by oil palm. Soil organic matter content was greater in the reference site than in the oil palm sites, suggesting higher organic matter input from grassland vegetation. Similarly, soil nitrogen content was higher in the reference site (0.23%) compared with the oil palm soils. In contrast, soil phosphorus content was lower in the reference site (12.39 ppm) than in the oil palm soils, where it ranged from 11.42 to 13.21 ppm, indicating enrichment of available phosphorus under oil palm cultivation. Overall, considerable variations in soil properties were observed in the oil palm plantations compared with the reference site. These results were further confirmed by dbRDA and cluster analyses, which indicated that the reference site, with its natural vegetation cover and minimal anthropogenic influence, formed a distinct subcluster characterized by higher organic matter content, lower bulk density, and comparatively lower phosphorus levels.

As stated, soil pH in the oil palm sites ranged from 5.45 to 5.50, indicating that the soil was acidic. This finding aligns with previous research showing that oil palm plantations generally develop acidic conditions in the pH range of 4.5 - 6.0 (Liyanagama et al., 2016). The lower pH in oil palm soil is correlated with the leaching of basic cations. Additionally, the extensive root system of oil palm trees absorbs large amounts of nutrients, thereby depleting basic cations in the surface and subsoil layers, leading to spatial variations in soil acidity. This nutrient removal, combined with rainfall-driven leaching, further increases soil acidity with increasing depth (Ulén, 2020). Soil electrical conductivity is negatively correlated with soil pH and remained within the optimal 20–50 $\mu S\ cm^{-1}$ range at all oil palm sites, consistent with reported values for oil palm plantations (Behera et al., 2020). Significant differences in electrical conductivity among sites can be attributed to spatial variability, soil compaction, and management practices. Electrical conductivity generally decreased with soil depth, as the low pH in oil palm soils reduced free ion availability, thereby lowering conductivity, which is consistent with the findings of this study.

Compared with previous studies, the recorded bulk density values for oil palm soil in this study fall within the suitable ranges for cultivated soils, but higher levels of compaction can reduce aeration and root growth (Kodikara et al., 2018; Nurulita et al., 2015). Particle density showed relatively small spatial differences among sites, with Site 3 reporting the highest value of 1.31 g cm^{-3}. The observed particle density values align with reported ranges for oil palm soil, suggesting minimal cultivation impact on this property (Tan et al., 2014). In contrast, soil porosity patterns reflect spatial variability in bulk density among the study sites. Site 1 had the lowest porosity (29.3%), while the values at Site 2 and Site 3 were within the optimal 40–60% range for oil palm growth as reported in previous studies (Sato et al., 2017).

Organic matter inputs in oil palm plantations mainly accumulate from fronds, empty fruit bunches, and crop residues, which are more abundant in Site 2 compared with other areas of the plantation. The organic matter content (around 5 - 6%) reported in the oil palm land in this study aligns with previous findings in Sri Lankan oil palm cultivations (Liyanagama et al., 2016) and in similar global studies (van Straaten et al., 2015). It was identified that the organic matter content decreases with soil depth due to reduced organic inputs below the surface, where plant residues accumulate and decompose. According to the results, the soil cation exchange capacity in Site 2 and Site 3 did not differ significantly from the reference site, likely due to similar clay and organic matter levels. Typically, oil palm soils have CEC values between 2–10 cmol kg^{-1} (Lubis et al., 2024), indicating that the soil in the studied plantation has good nutrient-holding capacity. Site 1 reported higher CEC (15.23 meq 100 g^{-1}), possibly due to land management practices such as tillage and clearing, which break down aggregates and expose new cation-exchange sites (Sung, 2016). Although acidic soils generally have lower CEC due to the increased solubility of aluminium and iron oxides that disrupt soil aggregates and reduce charge sites (Li et al., 2022), Site 1 recorded the lowest pH (5.47) but the highest CEC (15.23 meq 100 g^{-1}). This can be attributed to its relatively higher clay fraction and organic matter content, which provide permanent negative charges that compensate for the reduction in pH-dependent exchange sites.

Nitrogen levels in Site 1 and Site 2 did not show a significant difference but were higher than in Site 3 (0.17%) and the reference site (0.28%), likely due to differences in fertilizer application, crop uptake, and microbial activity. Oil palm trees are generally heavy nitrogen feeders, thereby reducing soil nitrogen through uptake (Carron et al., 2015). In this study, the higher nitrogen content in Site 3 most likely results from greater accumulation of nitrogen fertilizer in that site. The nitrogen content in oil palm soil in this study was reported as 0.1 – 0.2%, which aligns with findings from similar Sri Lankan oil palm estates at Hulandawa and Nakiyadeniya (Dissanayaka & Bandara, 2020). Nitrogen content decreases with soil depth due to leaching by percolating water.

Phosphorus levels differed significantly across oil palm sites but remained within the general range for oil palm soils of 10 – 50 ppm (Manorama et al., 2021). Site 3 had higher phosphorus content (13.21 ppm) than the reference site (12.39 ppm), likely due to fertilization practices, as phosphorus-based fertilizers increase soil phosphorus compared with unfertilized reference soils. Available phosphorus in the topsoil layer was classified as having moderate to high spatial variability, which aligns with the general observation that phosphorus exhibits high spatial variation within plantations. Phosphorus availability decreases in deeper layers due to fixation by soil particles (Tajudin et al., 2020). As discussed above, effective nutrient management, especially sustainable fertilization, is key to maintaining optimal nitrogen and phosphorus levels, along with efficient water management, for sustainable oil palm productivity (Pradiko et al., 2025).

The variations in soil properties between oil palm soil and grassland soil should be interpreted in relation to underlying soil mechanisms. Soil texture plays a vital role, as variations in many soil properties in both the oil palm plantations and the reference site are highly dependent on it. The soil in the oil palm plantations was classified as silty clay, whereas the reference site contained silty clay loam. Therefore, spatial variations in other parameters across different sites should be interpreted in relation to soil texture as an important influencing factor. As indicated, both soil textures share comparable physical characteristics, but their drainage and moisture retention capacities differ (Moradi et al., 2015). Moist, well-drained, humus-rich soils, such as sandy clay and silty clay, are considered optimum for oil palm cultivation (Rozieta et al., 2015). The silty clay soil at the oil palm site contained a higher proportion of clay than the reference site, which enhances water retention, nutrient-holding capacity, and cation exchange due to clay's high surface area and negative charge (Kumari & Mohan, 2021). In contrast, the higher sand content in the reference site soil improves drainage but reduces water retention, thereby making it less capable of sustaining moisture compared with the oil palm soil.

The grasslands, with lower organic matter decomposition rates and reduced nutrient depletion, maintained a higher pH, which supports better nutrient availability and microbial activity (Smith & Doran, 1997). The reference site reported higher electrical conductivity (65.50 µS cm^{-1}) than the oil palm soils, likely due to its higher pH and the greater accumulation of nutrients from organic matter decomposition in the grassland, whereas the oil palm sites reported more uniform nutrient uptake resulting from monoculture and controlled fertilization (Sung, 2016). Organic matter content in Site 2 (7.2%), which is in the middle of the plantation and in the reference site (7.3%), showed no significant difference, possibly due to similar natural soil conditions, higher levels of organic inputs, and minimal disturbance in both Site 2 and the reference site.

The variations in key physical parameters between the oil palm soils and the reference site soils, including bulk density, particle density, and porosity, should be discussed collectively. Soil bulk density was significantly higher in all oil palm sites (0.7 - 0.9 g cm^{-3}) than in the reference site (0.49 g cm^{-3}), indicating greater soil compaction from cultivation and machinery use. Site 1, located near the roadside with more anthropogenic activity, had the highest bulk density, while the reference grassland site showed minimal compaction. The findings also suggest that compaction near settlements may require conservation tillage or cover-crop strategies. Similarities between Site 1, Site 3, and the reference site reflect comparable proportions of silt and clay, which generally exhibit similar density characteristics. Higher porosity in the reference site is likely due to grassland vegetation and greater organic matter content, which is a typical characteristic of an abandoned grassland compared with cultivated land. Lower organic matter in the oil palm cultivation compared with the abandoned grassland contributes to reduced nitrogen content in the cultivated land.

As discussed, although soil properties in oil palm cultivation differed significantly from the reference site, these variations do not necessarily indicate soil degradation, as the soil's dynamic structure responds to management practices such as fertilization and irrigation. Important soil parameters, including soil acidity, bulk density, nitrogen, and phosphorus, were reported to be at optimal levels in the oil palm soils when compared with previous studies. Compared with findings from Malaysia, Indonesia, and West Africa (Shah & Wu, 2019) the Sri Lankan oil palm sites exhibited relatively stable soil properties over the short study period, whereas long-term plantations in other regions have often reported more pronounced changes. These differences may arise from variations in soil type, climatic conditions, and management intensity. The younger age and smaller scale of Sri Lankan plantations may also have limited the extent of cumulative soil degradation. Nonetheless, essential practices that support soil health over time, such as effective fertilizer application, continuous soil health assessments, organic matter recycling, and reducing soil compaction, need to be adopted to promote sustainable oil palm cultivation.

A key limitation of this study is that it focused mainly on the physical and chemical properties of soils, without considering biological aspects such as microbial activity, root interactions, or soil carbon dynamics. Extending this research to include these biological properties would provide a more holistic and integrated understanding of soil health under oil palm cultivation and substantially enhance the comprehensiveness of the findings.

5. CONCLUSION

This study analyzed the impact of oil palm cultivation on selected soil properties and the spatial variability between cultivated sites and a reference site. Significant spatial heterogeneity was identified within the plantation, influenced by inherent differences in soil parameters and localized management practices. Although the physicochemical soil parameters varied considerably across sampling sites, no consistent patterns indicative of continuous soil degradation were detected for the selected time period. These short-term findings suggest that oil palm cultivation, when managed carefully, may not immediately impair soil quality. Future research should incorporate multi-season, long-term monitoring across several oil palm estates with contrasting management practices to provide more robust insights into the sustainability of oil palm cultivation and its implications for soil health.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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