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Effects of intercropping, home gardening, and agrisilviculture on soil physicochemical properties in Malaysia

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Abstract Agriculture is essential for human survival, but unsustainable practices threaten its long-term viability. Intensive agricultural activities such as tillage, residue burning, and agrochemical use can lead to soil erosion and degradation. Sustainable practices such as intercropping, agroforestry, and home gardening are known to improve soil health and reduce environmental impact. This study investigates the effects of these practices on selected soil properties in Siburan, Sarawak. Soil samples were collected from three sites representing intercropping, agrisilviculture, and home gardening at depths of 0–20 cm, 20–40 cm, and 40–60 cm. The samples were analysed for moisture content, bulk density, pH, organic matter, organic carbon, total acidity, and exchangeable aluminium and hydrogen ions according to the standard procedure. Results show that soil moisture content in home gardening (57.89%) is significantly higher ($p < 0.05$) than in agrisilviculture (47.84%) and intercropping (25.60%). Organic matter content was also highest in-home gardening at 8.38%, while soil acidity and exchangeable aluminium were significantly elevated in home gardening soils compared to other practices. In contrast, the cations exchangeable capacity under home gardening is the lowest compared to agrisilviculture and intercropping. These findings emphasize the need to understand how different agricultural practices influence soil properties, providing practical insights for improving soil management strategies in Siburan, Sarawak.

Keywords Cations exchangeable capacity · Soil acidity · Soil properties · Sustainable agriculture practice

Introduction

Agricultural sector plays an important role in economic development and employment. According to Siddharta (2024) the agricultural sector contributed 7.8% to Malaysia's gross domestic product (GDP). In addition, the agricultural sector also plays an important role in poverty alleviation as most low-income people in Malaysia are engaged in agriculture (34% of the total number of low-income people) (Saari et al. 2013). The agricultural sector also plays a strategic role in ensuring food security. The National Agriculture and Food Policy 2021–2030 (NAP 2.0) prioritizes strengthening the agricultural sector, such as enabling modernization through smart agriculture and promoting research, development, commercialization and innovation, strengthening the value chain of agri-food products for the domestic and

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international market, developing talent and skilled labor, emphasizing sustainable practices and facilitating the business ecosystem, including land use, finance, infrastructure, investment and governance, are the key measures (Ministry of Agriculture and Food Security 2024).

Although agriculture is vital to human existence, there are many issues that threaten the ability of agriculture to meet human needs now and in the future, including climate change, biodiversity loss and pollution of water resources (Begum et al. 2020; Karp et al. 2012; Naseem et al. 2020; Zia et al. 2013). Soil degradation is one of the biggest problems caused by agriculture. Soil degradation is a long-term loss or decrease in soil productivity over time due to human activities or natural factors (Müller et al. 2023). In Malaysia, there are various types of land degradation, including forest land degradation, soil erosion, salinization, soil fertility declines and waterlogging (Ahmed and Boon 2023). Shifting cultivation is one of the possible causes of soil degradation in Malaysia, especially in Sarawak (Ahmed and Boon 2023). Soil erosion is caused by poor practices such as removal of vegetation cover, inappropriate ploughing and large fields with no boundary to slow down water movement (Alam 2014). According to Sofo et al. (2020), intensive agricultural activities can lead to soil erosion and degradation due to tillage, burning of residues and agrochemicals. The use of conventional tillage has an impact not only on the physical and chemical properties of the soil, but also on the biodiversity below and above ground (Domínguez et al. 2010). This will production and the sustainability of the agricultural sector, as agriculture is highly dependent on the soil.

Various agricultural practices have a significant impact on soil properties and the sustainability of crop production (Reilly et al. 2023). Intercropping, agroforestry and home gardeninging are among the best-known sustainable practices for soil health and reducing environmental impact. In intercropping, several plant species are grown simultaneously in one field to maximize resource use and reduce dependence on chemical inputs such as fertilizers and pesticides (Weih et al. 2022). Agroforestry, on the other hand, combines trees with crops and livestock to promote better soil utilization and improve soil fertility and water retention (Fahad et al. 2022). Home gardening, which often combines perennial crops, fruit trees and small livestock, plays an important role in improving soil organic matter and biodiversity (Wolle et al. 2021). Each of these practices the physical and chemical properties of the soil in different ways and provides numerous benefits such as increased organic matter, improved water retention and reduced soil compaction (Kaur et al. 2023; Pandey et al. 2024). However, improper management can lead to problems such as acidification, nutrient imbalances and lower crop yields (Zhang et al. 2016). Understanding the impact of these practices on soil properties is critical to promoting sustainable agriculture and ensuring long-term food security.

In Malaysia and Southeast Asia, intercropping, agroforestry and home gardening are practiced in different regions depending on local conditions and needs. In Malaysia, intercropping is commonly practiced in areas such as Cameron Highlands for vegetable production where crops such as cabbage, lettuce and beans are grown together to optimise land use and reduce soil erosion (Weih et al. 2022). Agroforestry is widespread in Sarawak and Sabah, where farmers combine crops such as pepper, rubber and fruit trees with forest species, contributing to better soil health and biodiversity (Fahad et al. 2022). In Java, Indonesia, practicing agroforestry helps conserve soil and restore degraded land (Mohamad Siarudin et al. 2021). In rural Malaysia, particularly in Kelantan and Terengganu, home gardening is widespread, where families grow vegetables, fruits and herbs for daily needs, reducing dependence on market produce (Wolle et al. 2021). These practices not only adapt to the local environment but also support sustainable livelihoods and the long-term.

Intercropping, agroforestry and home gardeningcombine traditional knowledge with innovative approaches to ensure long-term food production while protecting the environment. By adopting these practices, farmers can improve soil health, reduce pollution and increase resilience to climate change, benefiting both current and future generations. Malaysia has allocated RM6.42 billion for the Ministry of Agriculture and Food Security in Budget 2025, with sustainable agricultural practices being one of the key initiatives proposed (Bernama 2024). Despite this focus, the impacts of various sustainable agricultural practices on soil properties in specific local contexts remain poorly understood. Understanding these impacts is crucial as soil health has a direct influence on crop productivity, environmental sustainability and local livelihoods. This study seeks to answer the research question: What are the impacts of different sustainable agricultural practices on selected soil properties in Siburan, Sarawak?. Therefore, the aim of this study is to determine how these practices affect specific soil properties in Siburan to provide practical insights for improving soil management strategies in the region.

Materials and methods

Study sites

This study was conducted in the district of Siburan, approximately 32 km (19.88 miles) from Kuching City, the capital of Sarawak, Malaysia. The geographical coordinates of the study area are 1.3619° north latitude and 110.4045° east longitude, with an elevation 56 m above sea level. According to Malaysian Meteorological Department (2024), the dry season in Sarawak occurs in June or July and much of the monsoon season is in December to March. Generally, the rainfall distribution in Sarawak is around 2500–4000 mm annually with the highest rain in February (Malaysian Meteorological Department 2024). The weather conditions and tropical soil characteristics of this region provide a suitable environment for various agricultural practices. Three different sites covering about 0.25 acre were selected for this study, each representing a specific sustainable agricultural practice. At each site, a plot measuring 50 m × 50 m were established for soil sampling and analysis. Soil samples were collected using a completely randomized design, with sampling points randomly selected within each land-use practice to minimize spatial bias.

Site 1 (N 01°15.4446′ E 110°26.0234) represents intercropping, where cucumbers (*Cucumis sativus*) were grown with long beans (*Vigna unguiculata*) in alternating rows to optimize soil use and reduce pest infestation (Fig. 1a). Site 2 (N 01°15.5989′ E 110°25.8408) was identified as an agrisilviculture system combining crops and tree species such as rubber (*Hevea brasiliensis*), durian (*Durio zibethinus*), and various vegetables (Fig. 1b). Site 3 (N 01°14.3844′ E 110°25.9977) was a home gardening in a backyard where rubber trees were planted together with pineapple (*Ananas comosus*) and small livestock, including chickens and geese (Fig. 1c).

Soil samples collection

Soil samples were taken at three depths: 0–20 cm (surface layer), 20–40 cm (subsurface layer) and 40–60 cm (deep layer) for a more comprehensive analysis of soil properties in different horizons. Soil samples were collected using a soil auger and a core sampler to ensure consistency and accuracy. The randomized sampling method was used, with 4 replicates for each 50 m × 50 m plot to minimize sampling bias. At each depth, several subsamples were taken from different points within the plot to represent the overall

Fig. 1 Different types of agricultural practices **a** Intercropping practice (Long bean + Cucumber), **b** Agrisilviculture practice (rubber, durian, and various vegetables), **c** Home gardening (Rubber + pineapple + Geese + chicken)

soil condition. The soil samples were dried at room temperature and then crushed with pestle and mortar and carefully crushed to break up lumps. Large impurities such as stones, plant roots and other organic residues were removed manually. Finally, the samples were sieved through a 2 mm mesh sieve to obtain a uniform size of soil sample suitable for laboratory analysis.

Soil properties

The bulk density of the samples was determined using the method described by Tan (2005), the core sample method. The soil samples were oven-dried at 105 °C for 24 h and the oven-dried mass of the soil was divided by the volume of the soil (Eq. 1)

$$Soil\ bulk\ density\left(gcm^{-3}\right) = \frac{Weight\ of\ oven\ dry\ soil\ (g)}{volume\ of\ soil\ \left(cm^3\right)} \tag{1}$$

The moisture content of the soil was determined using the gravimetric method or oven drying technique where the difference in the weight before and after drying represents the amount of water present (Dutta 2015; Kashyap and Kumar 2021; Ungar et al. 1992). The soil samples were dried in an oven at 105 °C until they were constantly weighted and calculated using Eq. 2.

$$MC(\%) = \frac{Weight\ of\ water\ loss}{Weight\ of\ oven\ dried\ soil} \times 100 \tag{2}$$

The organic matter content of the soil was based on the gravimetric weight change associated with the high-temperature oxidation of organic matter. The difference in mass before and after ignition was calculated and the SOM was calculated using Eq. 3. According to Sikora and Stott (2015), approximately 58% of organic matter is composed of carbon. Therefore, we can estimate the percentage of SOM using the SOC% with the conversion factor 1.72 (derived from 100/58) and calculate the total organic carbon using Eq. 4.

$$OM = \frac{Weight\ before\ ignition - weight\ after\ ignition}{Weight\ before\ ignition} \times 100 \tag{3}$$

$$Organic\ carbon = OM \times 1.72 \tag{4}$$

The pH value of the soil was determined in potassium chloride (KCl) and water in a ratio (1:2.5) according to the method of Tan (2005). The total acidity and the concentrations of exchangeable aluminium (Al) and hydrogen (H) were determined using double titration method. The samples were extracted using 1 M potassium chloride (KCl) and then titrated with 0.01 M sodium hydroxide (NaOH) and 0.01 M hydrochloric acid (HCl). The concentrations of total acid, exchangeable Al and H are calculated using the formulae described by Rowell (1993/2014) as follows:

$$\begin{aligned} &Total\ acidity\ (meq/100g) = 0.01 \times \frac{Vol.\ of\ NaOH\ used\ (ml) \times 100}{soil\ sample\ (g)} \\ &Exchangeable\ Al\,(meq/100g) = 0.01 \times \frac{Vol.\ of\ HCl\ used\ (ml) \times 100}{soil\ sample\ (g)} \\ &Exchangeable\ H\,(meq/100g) = Total\ acidity - Exchangeable\ Al \end{aligned} \tag{5}$$

The cations were extracted using the ammonium acetate shaking method as outlined by Page (1982). Extraction was carried out using 1 M ammonium acetate (NH_4OAc) adjusted to pH 7.0, followed by shaking at 180 rpm for 6 h. The concentration of the exchangeable potassium (K^+), sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined using Absorption Spectrophotometer (AAS) (iCE 300, Thermo Fisher Scientific®, NSW, Australia). The exchangeable cations were calculated using the formula described in Eq. 6;

$$\begin{aligned} &\text{Exchangeable ions (cmol(+)/kg)} \\ &= \text{ ion concentration (mg/kg) / ion mg per cmol/kg} \end{aligned} \tag{6}$$

Data analysis

The data were analysed using Statistical Analysis Software Version 9.2 (SAS, 9.2). Before the main analysis was performed, the data were checked for normality and homogeneity of variance to fulfil the assumptions of the parametric tests. The Shapiro–Wilk test was used to assess the normality of the data distribution, while the Levene test was used to assess the homogeneity of variances between groups. Post-hoc comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to determine which groups showed significant differences. The significance level was set at $p < 0.05$ for all statistical tests. This robust statistical approach ensures the reliability of the results and enables a comprehensive comparison of soil properties between the intercropping, agrisilviculture and home gardening systems.

Results

The soil in the home gardening (57.89%) has the highest moisture content, followed by agrisilviculture (47.84%) and finally intercropping (25.60%). All three locations differ significantly in terms of moisture content. Regarding the bulk density of the soil, the soil under intercropping practice (1.09 g cm^{-3}) is significantly higher than in agrisilviculture farming (0.67 g cm^{-3}) and home gardening (0.58 g cm^{-3}). As shown in Table 1, the soil in intercropping had the highest organic matter and organic carbon content, 8.38% and 4.86% respectively. However, there is no significant difference in the organic matter and organic carbon content of the soil compared to the soil in the home gardening. The soil under practice is significantly lower in terms of organic matter and practice and home gardening.

Figure 2 shows that the soil at 0–20 cm under agrisilviculture crops has the highest soil pH, with a pH of 5.98, which is significantly higher than that of a home gardening (5.22), but not significantly higher than that of intercropping (5.75). At 20–40 cm, however, there is no significant difference in soil pH between all sites. At 40–60 cm, on the other hand, the soil under the home gardening with a pH value of 6.40 is significantly lower than the intercropping (6.90) and agrisilviculture (7.20).

At all depths, the acidity of the soil in the home gardening (0–20 cm = 0.30 meq/100g; 20–40 cm = 0.18 meq/100g; 40–60 cm = 0.59 meq/100g) is significantly higher

Table 1 Soil properties under different agriculture practices. Values are expressed as mean ± standard deviation, and significances between the practice's differences (5% significance or $p < 0.05$) are conducted by Tukey's test after one-way ANOVA

Variables	Practice		
	Intercrop	Agri-silviculture	Home gardening
Soil moisture (%)	25.60 ± 0.52^{c}	47.84 ± 0.40^{b}	57.89 ± 0.67^{a}
Bulk density (gcm^{-3})	1.09 ± 0.09^{a}	0.67 ± 0.10^{b}	0.58 ± 0.16^{b}
Organic matter (%)	5.72 ± 0.78^{b}	8.38 ± 0.65^{a}	8.16 ± 0.03^{a}
Organic carbon (%)	3.32 ± 0.45^{b}	4.86 ± 0.38^{a}	4.74 ± 0.02^{a}

Means with different letters within the same row are significantly different ($p < 0.05$)

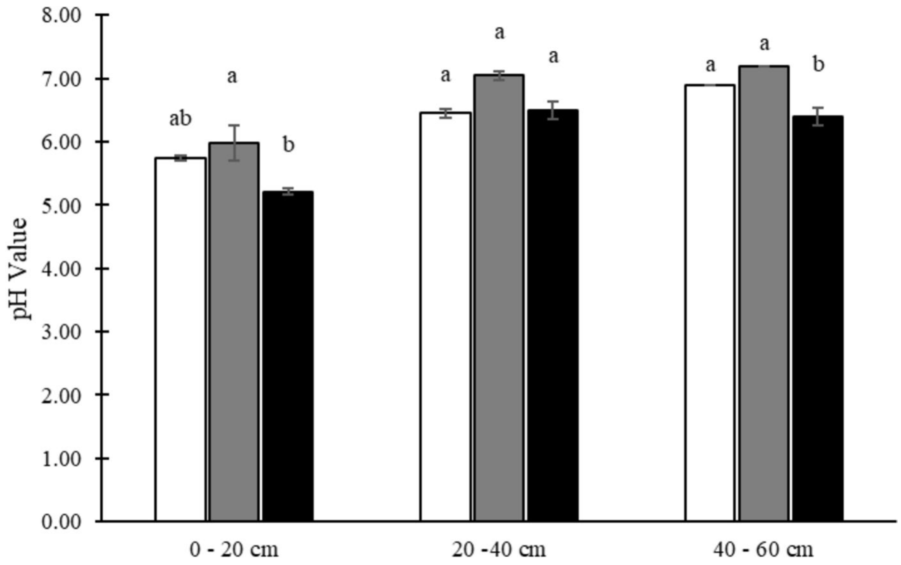


Fig. 2 Soil pH under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. 0–20 cm (0–20 cm), 20–40 cm (20–40 cm), and 40–60 cm (40–60 cm). The pH values were compared between different agriculture practices for each depth. The bar represents the standard deviation and mean with different letters is significantly different ($p < 0.05$)

than in intercropping and agrisilviculture (Fig. 3). There is no significant different in term of soil acidity at all depth between intercropping and agrisilviculture.

In terms of exchangeable aluminium ion ($Al^{3+)}$, the soil under the home gardening is significantly higher at 0–20 cm (0.29 meq/100 g), 20–40 cm (0.05 meq/100 g) and 40–60 cm (0.42 meq/100 g) compared to the other practices (Fig. 4).

Soil exchangeable hydrogen ions (H^+) in home gardening also significantly higher at all depths 0–20 cm (0.21 meq/100 g), 20–40 cm (0.11 meq/100 g) and 40–60 cm (0.14 meq/100 g) than in the intercropping and agrisilviculture practices (Fig. 5).

At 0–20 cm, the exchangeable potassium ion (K^+) in the soil under agrisilviculture (0.105 cmolc/kg) is significantly higher than in the other practice, followed by the soil under intercropping (0.073 cmolc/kg) and finally the soil under home gardening (0.032 cmolc/kg) with the lowest exchangeable K^+. Exchangeable K^+ in intercropping and agrisilviculture at the depth 20–40 cm (Intercropping = 0.071 cmolc/

Fig. 3 The soil acidity under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. 0–20 cm (0–20 cm), 20–40 cm (20–40 cm), and 40–60 cm (40–60 cm). The total acidity was compared between different agriculture practices for each depth. The bar represents the standard deviation and mean with different letters is significantly different ($p < 0.05$)

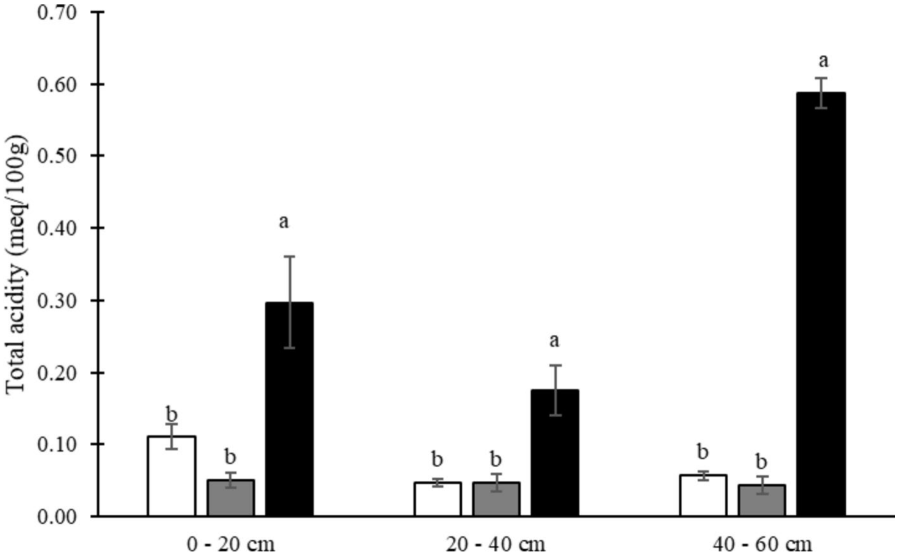


Fig. 4 Exchangeable aluminium ion (Al^{3+}) under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. 0–20 cm (0–20 cm), 20–40 cm (20–40 cm), and 40–60 cm (40–60 cm). The exchangeable Al^{3+} was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

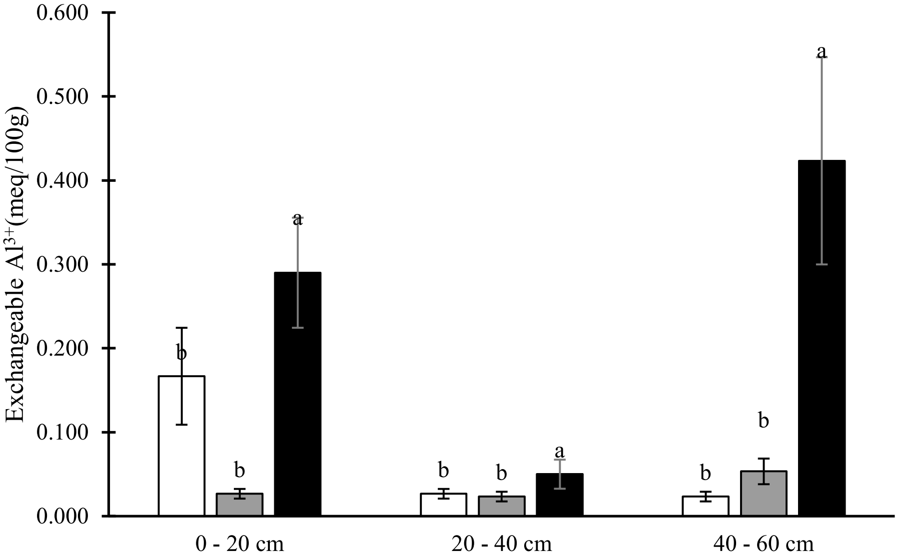
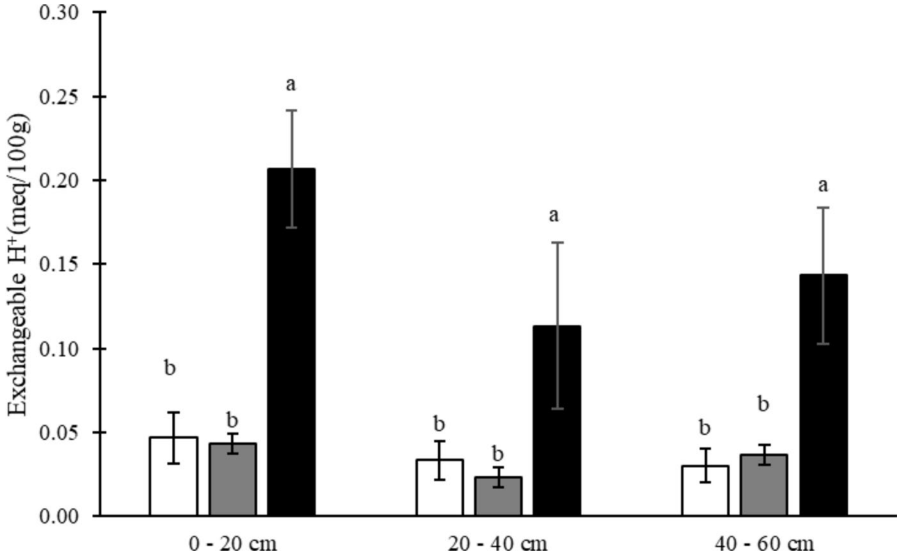


Fig. 5 Exchangeable hydrogen ion (H^+) under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. 0–20 cm (0–20 cm), 20–40 cm (20–40 cm), and 40–60 cm (40–60 cm). The exchangeable H^+ was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

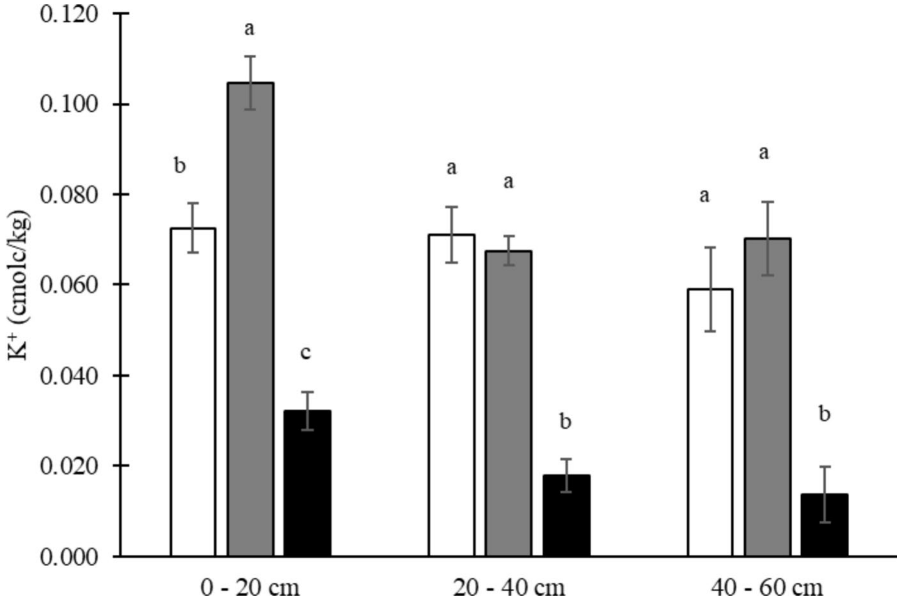


kg; Agrisilviculture = 0.068 cmolc/kg) than in home gardening (Fig. 6).

At a depth of 0–20 cm, the content of exchangeable sodium ions (Na^+) is significantly higher in agrisilviculture (0.057 cmolc/kg) than in home gardening (0.041 cmolc/kg), but not significantly higher than in intercropping (0.047 cmolc/kg) (Fig. 7). At depths 20–40 cm, the exchangeable Na^+ in home gardening is significantly lower (0.039 cmolc/kg) compared to the other practice. However, there is no significant difference in the exchangeable Na^+ among all practice at the depth of 40–60 cm.

The exchangeable magnesium ion (Mg^{2+}) under agrisilviculture (0.561 cmolc/kg) is significantly higher than that under home gardening (0.242 cmolc/kg), but not significantly higher than that under intercropping (0.425 cmolc/kg) at 0–20 cm (Fig. 8). At 20–40 cm, the soil under agrisilviculture (0.516 cmolc/kg) has the highest exchangeable Mg^{2+}, followed by intercropping (0.374 cmolc/kg) and the

Fig. 6 Exchangeable potassium ion (K^+) under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. The exchangeable K^+ was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)



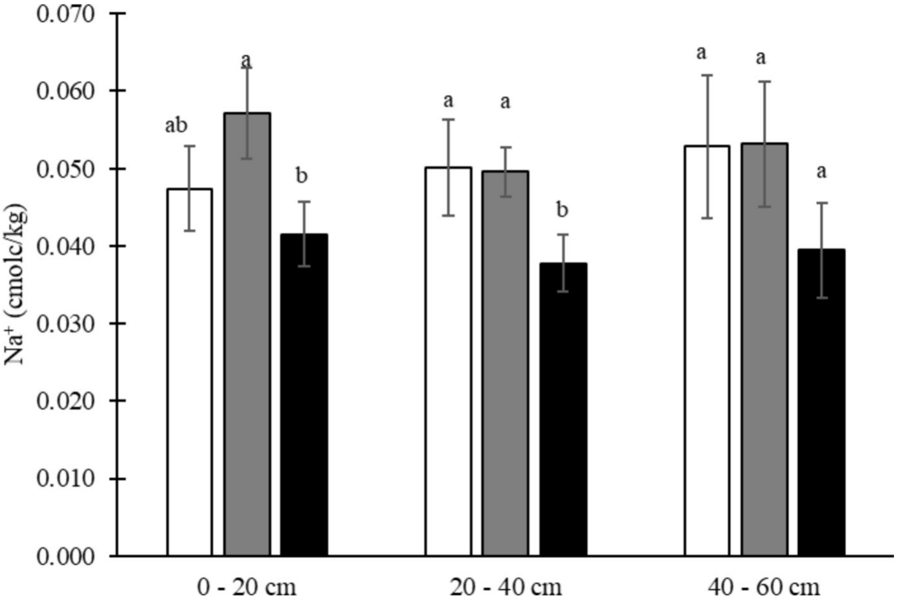


Fig. 7 Exchangeable sodium ion (Na^+) under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. The exchangeable Na^+ was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

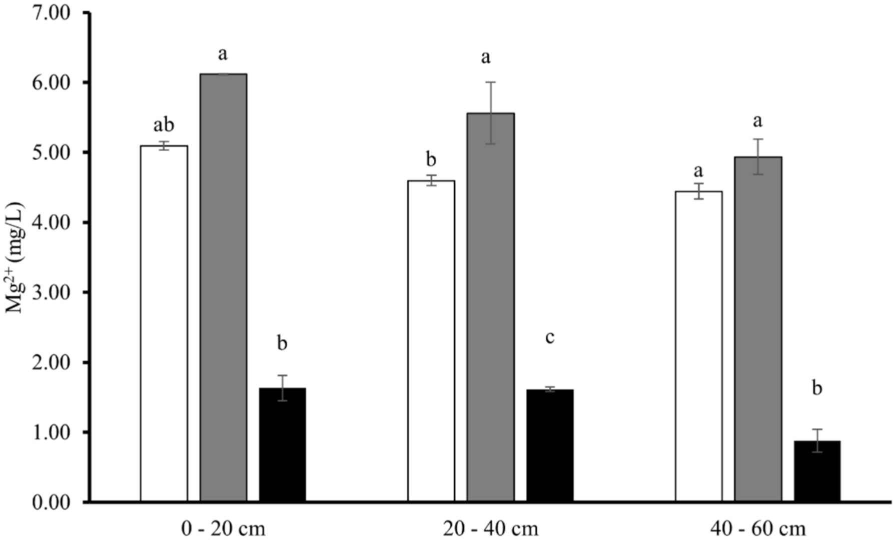


Fig. 8 Exchangeable magnesium ion (Mg^{2+}) under different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) at different depths. The exchangeable Mg^{2+} was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

home gardening (0.111 cmolc/kg) with the lowest exchangeable Mg^{2+}. At 40–60 cm, the exchangeable Mg^{2+} in the soil under intercropping (0.386 cmolc/kg) and agrisilviculture (0.504 cmolc/kg) is significantly higher than in the home gardening (0.107 cmolc/kg).

As for exchangeable calcium ions (Ca^{2+}) depths 0–20 cm, the exchangeable calcium (Ca^{2+}) in intercropping (1.599 cmolc/kg) and agrisilviculture (1.468 cmolc/kg) are significantly higher than in the home gardening (0.929 cmolc/kg) (Fig. 9). Meanwhile, at 20–40 the soil under intercropping practice (1.608–cmolc/kg) has the highest exchangeable Ca^{2+} followed by agrisilviculture (1.478 cmolc/kg) and finally the home gardening (0.522 cmolc/kg) with the lowest exchangeable Ca^{2+}. At depth 40–6-cm, exchangeable Ca^{2+} under intercropping (1.568 cmolc/kg) and agrisilviculture (1.436 cmolc/kg) are significantly higher than home garden (0.646 cmolc/kg). (Fig. 10)

There is no significant difference in terms of effective cations exchangeable capacity (ECEC) at 0–20 cm under all practices. At 20–40 cm, the ECEC under

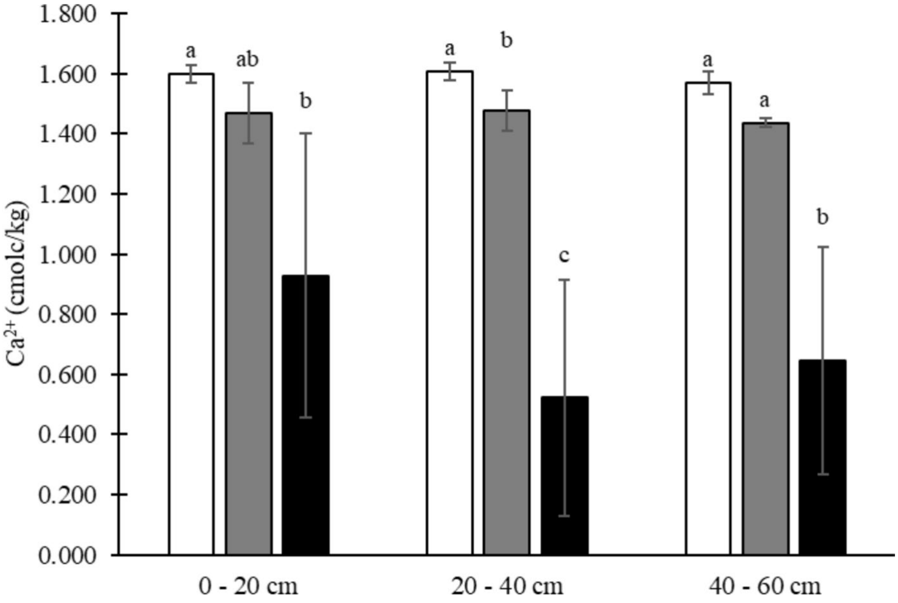


Fig. 9 Exchangeable calcium ion (Ca^{2+}) under different agriculture practices practices (White: intercropping; Grey: agrisilviculture; Black: home gardening at different) at different depths. The exchangeable Ca^{2+} was compared between different agriculture practices for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

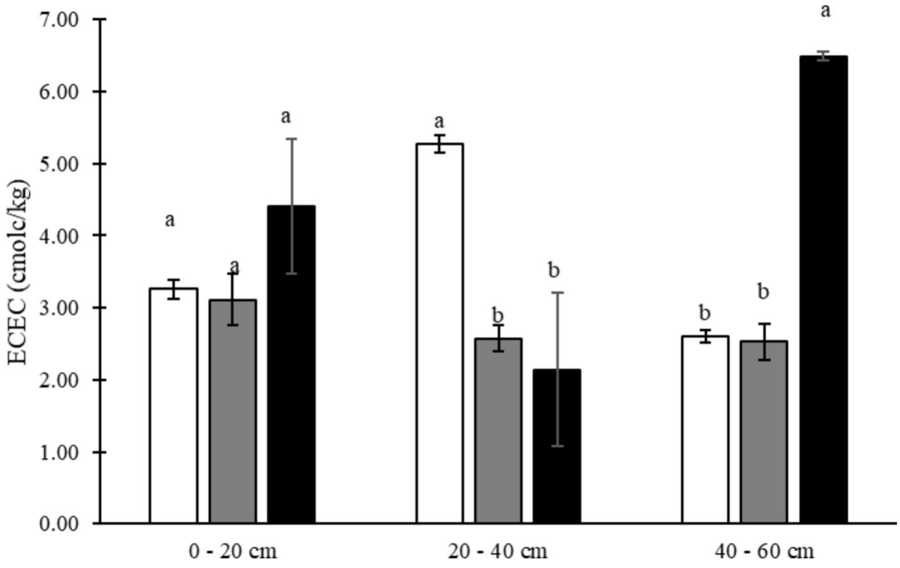


Fig. 10 Effective cations exchangeable capacity (ECEC) under different agriculture practices at different depths. The cations exchangeable capacity (CEC) was compared between different agriculture practices (White: intercropping; Grey: agrisilviculture; Black: home gardening) for each depth. The bar represents the standard deviation and means with different letters is significantly different ($p < 0.05$)

intercropping is significantly higher (5.27 cmolc/kg) compared to the other practices. However, at the depth of 40–60 cm ECEC under home gardening (6.49 cmolc/kg) is significantly higher compared to the other practices.

Discussion

Based on the results, the significant differences in soil moisture content could be due to better vegetation cover and the accumulation of organic matter tend to retain more moisture than systems with less soil cover, such as intercropping. The presence of trees, shrubs, and understory crops in mixed agroforestry systems establishes a multi-tier canopy that limits direct sunlight and wind at the soil surface. This microclimatic buffering reduces evaporation rates and improves soil water retention, ultimately contributing to higher moisture content compared to less vegetated systems. Study in Cambodia by Ehrenbergerová et al. (2021) also explained the soil moisture under shaded areas is higher because the tree shade reduces exposure to sunlight and wind which reduces the evaporation. Kaur et al. (2023) also mention that agroforestry provides tree canopies that reduce evaporation and transpiration from the soil and plants, will efficiency and ensure optimal soil moisture.

The results also show that the soil under the agroforestry system (home gardening and agrisilviculture) contains more organic matter and carbon. The high accumulation of organic matter in agroforestry systems could be due to the leaf litter and plant debris from trees and the diverse vegetation. The minimal disturbance of the soil that allows natural accumulation and decomposition of organic matter, and the higher microbial activity that supports nutrient cycling and improves soil fertility (Pandey et al. 2024). The diverse vegetation of the agroforestry system also ensures a continuous process of decomposition of organic matter in the soil (Dollinger and Jose 2018). The increase in organic matter input will enrich the organic carbon in the soil, which could improve nutrient availability and soil fertility, which would have a positive impact on soil health (Dollinger and Jose 2018). Poultry movement can increase surface compaction and reduce infiltration locally; however, in the studied home garden systems, this effect is likely offset by continuous organic residue inputs, litter cover, and root activity, which improve soil structure, aggregation, and water-holding capacity. As a result, the net effect on soil moisture reflects the balance between compaction from animal trampling and structural improvement from organic matter inputs, with the latter likely dominating under low-intensity, small-scale home garden management.

A high proportion of organic matter in the agroforestry system led to a low bulk density, as the result of our study shows, in which the bulk density in the agroforestry system (home gardening and agrisilviculture farming) is significantly lower than the bulk density in intercropping. This is consistent with the results of the studies conducted in Yemen by Aldeen et al. (2013), who found that an increase in organic matter led to a decrease in the bulk density of the soil. The study by Athira et al. (2019) reported that bulk density has a negative relationship with soil organic matter, with bulk density being lower when soil organic matter is higher. Pandey et al. (2024) also mentioned that agroforestry systems can improve soil physical properties by reducing soil bulk density and compaction. This suggests that the agroforestry system appears to maintain soil structure, create favorable conditions for root development and possibly help maintain crop productivity (Chavez et al. 2024; Fahad et al. 2022; Kaur et al. 2023). High soil bulk density is usually associated with soil compaction, which leads to reduced pore space for air and water and can negatively affect root development and overall plant productivity (Shaheb et al. 2021; Watson and Kelsey 2006).

Our results show that the soil under home gardening recorded the lowest pH. The lower pH in home gardening is likely due to the high accumulation of organic material from tree or shrub litter and root biomass, which lower the soil pH (Wolle et al. 2021). The deeper root systems in agrisilviculture can enhance nutrient cycling and help stabilise soil pH. Jiang et al. (2018) also noted that soils with high organic matter have better acid-buffering capacity due to improved cation exchange capacity, while Dvořáčková et al. (2022) highlighted the role of organic matter in stabilising soil buffering and pH regulation.

Although soil acidity under the home gardening recorded the highest compared to the other practice, the acidity level remained within the moderate range and below thresholds typically associated with aluminium toxicity and severe soil chemical constraints (Brady and Weil 2017). High exchangeable acidity under home gardening could be driven by rapid decomposition of organic matter, which releases organic acids. In home gardening integrating chickens and geese, repeated deposition of poultry manure can significantly influence soil acidification, particularly in surface soils. Continuous deposition of poultry droppings and manure in mixed crop livestock home gardening influenced soil acidification processes through enhanced nitrogen inputs and subsequent nitrification, which releases hydrogen ions and promotes leaching of base cations such as Ca^{2+} and

Mg^{2+} (nitrate–H^+ mechanism) into deeper soil layers, thereby increasing exchangeable acidity over time despite initial base cation inputs from the manure itself. Poultry manure is nitrogen-rich and can contribute to soil chemical changes driven by nitrogen transformations and organic matter decomposition, with long-term effects on soil pH and soil nutrient dynamics depending on management and environmental conditions (e.g., nitrification and cation leaching) (Rayne and Aula 2020; Doydora et al. 2011). Notably, exchangeable Al^{3+} peaked at 20–40 cm in home gardening and was significantly higher than in other systems, indicating aluminium mobilisation at this depth possibly linked to nutrient leaching or distinct root activity patterns. Overall, these results indicate that home gardening is more prone to acidification, whereas agrisilviculture promotes stronger buffering capacity. Although intercropping is moderately acidic, its elevated Al^{3+} levels at 20–40 cm suggests a need for monitoring.

Although the soil under home gardening exhibited high organic matter (OM) accumulation, they reported the lowest cation exchange capacity (CEC), which was consistently the lowest across all depths compared to agrisilviculture and intercropping. Home gardening soils also contained the lowest concentrations of exchangeable K^+. Agrisilviculture recorded the highest K^+ concentration at 0–20 cm, although differences at deeper layers were not significant. This may indicate improved K^+ retention under agrisilviculture, possibly due to organic matter inputs and reduced leaching. Regarding Mg^{2+} and Ca^{2+}, agrisilviculture consistently showed the highest concentrations, while home gardening had the lowest. Low exchangeable Al^{3+} that occupied the exchange sites and neutralized the negative charge in soil the lowered the ECEC. Although poultry manure in home garden may initially supply base cations and temporarily increase soil pH, prolonged nitrogen cycling and leaching often result in net soil acidification over time (Marschner 2012). In addition, localized accumulation of droppings and soil disturbance caused by poultry foraging can intensify surface soil acidification and create spatial heterogeneity in soil pH and exchangeable Al^{3+}. These effects are particularly pronounced in acidic, variable-charge soils, where pH-dependent charge development limits effective cation exchange capacity despite high organic matter inputs (Brady and Weil 2017; FAO 2017).

Implication of different agriculture practices on soil management practices

The results of this study provide crucial insights into sustainable soil management practices for different agricultural systems in Siburan. Agrisilviculture farming and home gardening showed the most positive effects on soil health, especially in terms of organic matter, moisture content and reduced bulk density, emphasising their potential as a sustainable option for smallholder farmers. However, the higher soil acidity and increased levels of exchangeable aluminium and hydrogen ions in the home gardening suggest that targeted soil management practices such as liming and organic amendments are needed to maintain soil pH and fertility. In intercropping systems, improved organic matter management and the use of mulch or cover crops could help to reduce bulk density and better retain moisture in the soil.

These findings emphasise the importance of promoting sustainable practices through farmer education and policy support to encourage the adoption of agrisilviculture farming and home gardening while addressing site-specific soil management issues. Integrating these practices into local agricultural policies can contribute to long-term soil fertility and sustainable agricultural productivity in the region. The higher organic carbon under agrisilviculture indicates greater carbon sequestration potential in that system, aligning with the idea that tree-integrated farming can store more carbon in soil (Yasin et al. 2019).

Conclusion

The findings of this study demonstrate that agrisilviculture provides superior soil chemical and physical conditions compared with home gardening and intercropping systems, highlighting its potential as a sustainable land-use strategy for improving soil health in tropical environments. The higher organic matter, organic carbon, and moisture content observed under agrisilviculture underscore the importance of maintaining continuous plant cover and organic inputs to enhance soil structure and nutrient retention. In contrast, the greater soil acidity and elevated exchangeable aluminium in home gardening systems indicate a need for targeted soil amendments, particularly liming and balanced fertilization, to prevent base cation depletion and aluminium toxicity. Although intercropping remains a viable sustainable practice, the results suggest that its effectiveness can be improved through additional conservation measures such as residue retention, mulching, and reduced tillage to minimize moisture loss and organic matter decline. From a policy perspective, these findings support the promotion of integrated agroforestry-based systems, site-specific soil fertility management, and farmer extension programs that emphasize soil pH management, organic matter enhancement, and sustainable input use to ensure long-term agricultural productivity and environmental sustainability.

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Author contribution Conceptualization, data curation, material preparation, data collection and analysis, writing original draft were done by Jacklin Anak Mathew. Supervision; data curation; formal analysis; writing review and editing were performed by Mohamad Hilmi Ibrahim. All authors contributed to the study conception, design, commented on previous versions of the manuscript and approved the final manuscript.

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Data availability For inquiries regarding data availability, please contact the author directly.

Declarations

Conflict of interest The authors declare no competing interests.

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