Journal of Science, Innovation and Creativity
Vol. 3 No. 1 (2023): ISSN (Online): 2958-454X
DOI: https://doi.org/10.58721/jsic.v3i1.663

Integrating *Cordia Africana* Trees on Farms Differentially Improves Soil Properties in Small Holder Farms in Kirinyaga County, Kenya

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Article History
Received: 2024-03-16
Revised: 2023-07-09
Accepted: 2023-07-19
Published: 2023-08-08

Keywords
Agroforestry
Cordia africana
Ecosystems
Forest
Soil Fertility

How to cite:
Kamau, M., Kinyanjui, M & Kamiri, H. (2024). Integrating *Cordia Africana* Trees on Farms Differentially Improves Soil Properties in Small Holder Farms in Kirinyaga County, Kenya. *Journal of Science, Innovation and Creativity*, 3(1), 22-33.

Abstract
Tree-based solutions are more efficient in nutrient cycling in farming systems and hence ideally suited for impoverished farmers experiencing food insecurity. Agroforestry trees have a positive effect on soil fertility through litter fall by the canopies compared to that of the adjacent open fields. Field sampling involved selecting mature *Cordia africana* trees from ten farms and collecting soil samples at varying distances from the tree trunks and at two depths (0-15 and 15-30cm). For each selected farm, soil samples were collected at three sampling points defined by distance from the tree base thus: - 5M (under the tree canopy), 11M (at the edge of the crown), and 30M (from the tree's influence. Laboratory analyses measured concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, and organic carbon. The soil parameters investigated (Nitrogen, Phosphorus, Soil organic carbon, Potassium, and Calcium) were significantly higher in the topsoil than in the subsoil. The horizontal effect of trees with increasing distance from the tree on soil nitrogen, organic carbon, and phosphorus is minimal, the effect being more on vertical distribution (across depth). Differences in nutrient contents in soil nutrient variables between agroforestry and cropped land showed that soil nutrients within the *Cordia africana* system were higher than those under cultivated land implying that *Cordia africana* has a positive effect on soil quality. Thus, the study emphasizes the adoption of *Cordia africana* in agroforestry practices with a view to increase soil fertility and improve crop yields in sustainable farming. There is therefore need for the formulation of appropriate measures of soil management based on the characteristics of the sites.

Introduction
Agroforestry is considered an alternative solution to address challenges in sustainable forest management, especially in forest areas adjacent to community settlements (Singh et al., 2021), and enhancing communities' resilience to climate change, food security and income generation (Kumar et al., 2024). However, a major drawback to the community's resilience to food security lies in low and declining soil fertility in major agricultural and forest systems. Native trees in agroforestry systems sustain soil properties by building soil nutrient pools and recycling nutrients. The soil's chemical

properties are significantly better under the canopies of agroforestry trees than on cropped land (Gota et al., 2024).

Agroforestry is a proven model of an integrated sustainable land use system which can enhance agricultural productivity (Alao & Shuaibu, 2013). Furthermore, agroforestry practices significantly affect soil erosion management and improve moisture retention (Atangana et al., 2014). Some trees provide timber for household use, such as fuel wood and construction poles (Báder et al., 2023), as well as medicinal plants (Rao et al., 2004), edible fruits, leaves, roots and steam and feed for livestock (Leakey, 1999); shelter and ameliorating microclimates (Newaj et al., 2013). The rapid exhaustion of soil nutrients in smallholder farms could be managed by including native agroforestry tree species in the farms in diverse architecture (Nair, 2011) Bayala & Ouedraogo, 2008; Sileshi et al., 2020).

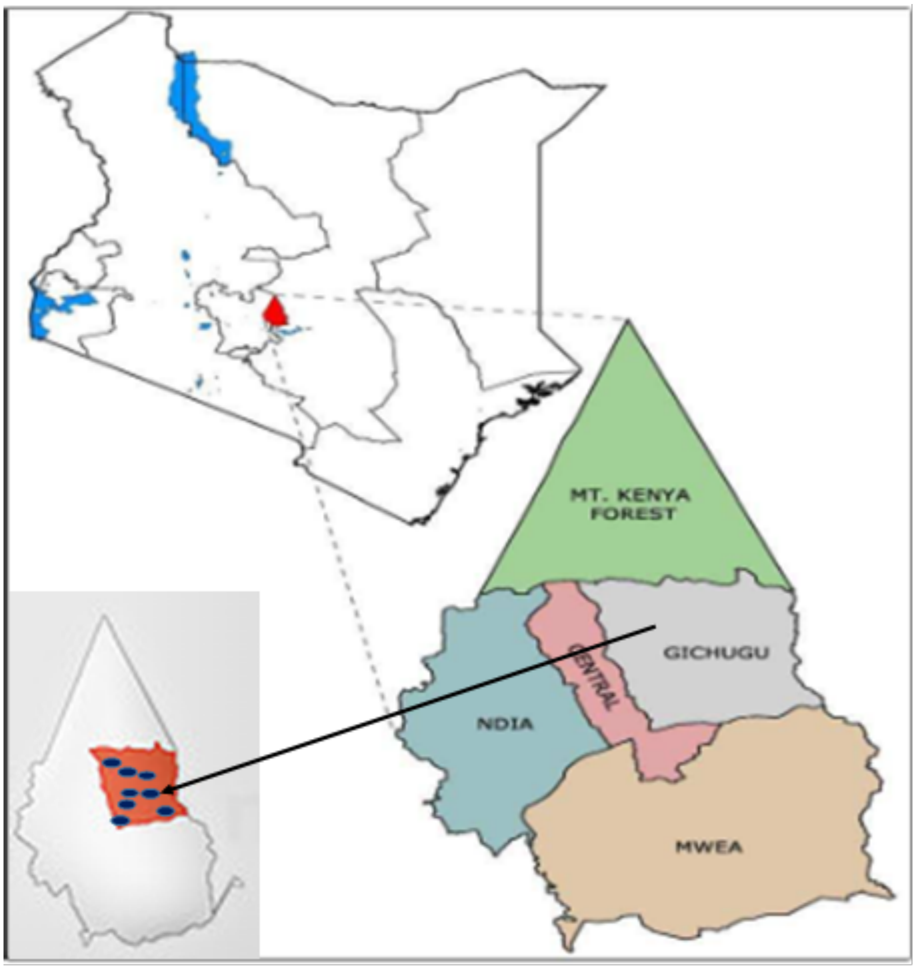
In Kenya, the adoption of trees on farms under the agroforestry system is mainly supported by large farms or institutions (Reppin et al., 2020). In countries like Ethiopia, agroforestry is widely adopted, especially in coffee-growing areas, with many attributable benefits in crop production and soil fertility (Octavia et al., 2023; Alemu, 2016). However, as noted globally, these systems can enhance soil fertility through various mechanisms, such as leaf litter accumulation, nutrient cycling, and soil erosion control (Nair et al., 2011). In the central highlands of Kenya, such native agroforestry trees include *Etyihriila abyssinica, Crolon megalocarpus, Croton macrostachyus*, *Pygeum africanum Kigelia Africana*, *Markhamia lutea*, *Commiphora zimmermanni* and *Cordia Africana,* among others (Reppin et al., 2020).

Previous studies have highlighted the potential of *Cordia africana* to improve soil fertility in agroforestry contexts. For instance, Etafa (2022) noted that *Cordia africana* can acquire nutrients through deep root penetration and redistribute them to the topsoil via leaf litter decomposition. Similarly, Ndlovu (2013) found that integrating *Cordia africana* in agricultural systems enhanced soil nitrogen status and maize productivity. However, there is limited information on the spatial distribution and variability of soil nutrient contents beneath *Cordia africana* canopies in smallholder farming systems of Kenya's central highlands. This study was carried out to assess the distribution of soil nutrients under *Cordia africana* canopies by comparing soil nutrient levels at different depths and various distances from the canopy.

Methods

This study was carried out in Gichugu, Kirinyaga County. The County is between 0^{0}30’46S and 37^{0}15’21E at 2100 m above sea level (Figure 1). The area receives an average annual rainfall of 1200 mm with a minimum temperature of 180C and a maximum temperature of 26.9^{0}C. The county has a high agro-economic potential due to its favourable climate. Land use in the study area comprises natural and planted forests, livestock and beekeeping and rain-fed agriculture. However, food production and forest cover have declined due to the changing land use and livelihoods. The major soils are described as nitisols with dark reddish brown to dark colour (Sombrek et al., 1982).

Figure 1. A map the study area showing Kirinyaga County Administrative Divisions and inset random farms selected for soil sample collection in Gichugu subcounty



Experimental design and field layout

The study was carried out on farmers' fields to compare the soil property status under native trees traditionally retained on farms (*Cordia Africana)* against uncultivated fields outside the canopy cover of each tree. The study site was purposefully selected based on the predominance of *Cordia Africana* agroforestry systems and agricultural potential. Studies by (Njeru et al. 2011) have shown that soil nutrient contents in the study area have been on the decline, particularly nitrogen content in cultivated soils, which have been reported to be between 0.06-0.5%, while phosphorus, potassium, magnesium and pH have been influenced by land management. A reconnaissance survey was conducted to identify the smallest administrative units and individual farms with *Cordia africana* trees. Farms were selected from three sub-locations (Kanjuu, Ngiriambu and Ngerwe). In each farm, all the agroforestry trees were recorded, and observation was done on the location (distance) of *Cordia africana* trees from the cropped area or grazing land. Proportional allocation of sample trees was done based on land size and ranged from 3-6 trees. The selected trees were mature, ranging from 30 to 100 years old. This age range was chosen to ensure that the trees had established themselves and contributed to the soil fertility dynamics over an extended period.

Selection of sampling points

For each selected farm, soil samples were collected at three sampling points defined by distance from the tree base: 5M (under the tree canopy), 11M (at the edge of the crown), and 30M (from the tree's influence).

At each sampling point, soil samples were collected at two depths: 0-15 cm (topsoil) and 15-30 cm (subsoil). Six soil samples were collected using a soil auger and trowel at each depth and mixed thoroughly to create a composite sample. For each point, three replicates were collected. The samples were packed in clear polythene bags and then placed in labelled khaki paper bags for transportation to the National Agriculture Research Laboratories (NARL) in Kabete for macro and micronutrient analysis. Dried leaf litter fall samples of *Cordia africana* were collected under the selected trees, bilked together, and analysed for tissue content and nutrients. Soil samples were air-dried, ground to a fine powder, sieved through a 2 mm mesh and subjected to nitrogen, organic carbon, total phosphorus, potassium and calcium analysis following standard methods (Okalebo et al., 2002). All the data collected was subjected to analysis of variance (ANOVA) using the SPSS. Soil nutrient data was presented as means. The ANOVA was used to determine if there were significant differences in the measured soil fertility parameters (nitrogen, phosphorus, potassium, calcium, and organic carbon) among farms, distances from the *Cordia africana* tree, and soil depths.

Results

From the survey carried out in the study area, eleven tree species were identified as common, native trees which were spread in the farms (Table 1).

Table 1. Common traditional Agroforestry Trees found in the study area

Tree	Local name	Common Uses
Etyihriila abyssinica	Mubuli or Inuhuii	Living fence, medicinal uses
Crolon megalocarpus	Mukinduri	Poles, boundary marker, cattle shade
Croton macrostachyus	Mutundu	Poles, medicinal uses, and boundary markers
Ficus niaiale	Mugumo	Ceremonial and medicinal uses
Pygeum africanum	Mweria	Mortars, pestles, poles, building timber, and cattle enclosures
Kigelia africana	Muratina	Fruit used as a fermenting agent
Markhamia lutea	Muu	Poles, building timber, and firewood
Bridelia micanthra	Mukoigo	Poles, timber, and firewood
Ricinus communis	Mubariki	Castor seed and oil (profuse seeds, fast growing)
Cordia abyssinica	Muringa	Beehives, stools, mortars, well covers, and building timber
Commiphora zimmermanni	Mukungugu	Vine props, poles, utensils

Traditional agroforestry practices in Kirinyaga County involve integrating these trees with crops and livestock, thus contributing to the provision of fuel wood, timber, biodiversity conservation, medicinal uses, soil quality improvement and food (fruits). However, proper management of the trees, including pruning and pollarding, is essential for maintaining the system's productivity and ecological benefits.

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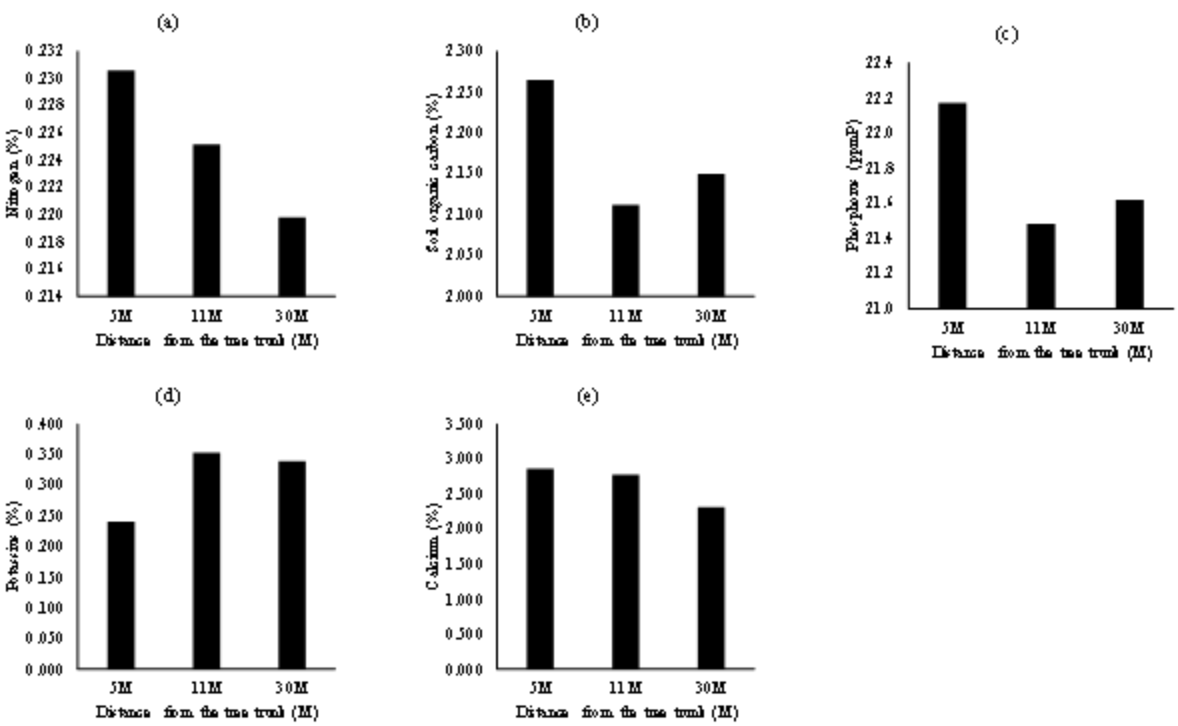
Variations of soil nutrient contents under *Cordia africana* canopy

A survey of farms in Kirinyaga County was conducted to establish the existence and growth areas of *C. africana* trees in the farms. *Cordia africana* had a mean density of 25 trees ha $^{-1}$, ranging from 10 to 35 trees ha $^{-1}$ across the farms under study. This density implies that *C. africana* is dominant in the region's agroforestry systems. The extent of farmers' adoption of *C. africana* was at a moderate to high level at 65% of the farmers in Kirinyaga County. Some of the reasons farmers gave as to why they included *C. africana* on their farms included timber production, provision of shade for crops, and extra income from fruits and honey. Their presence in 65% of the surveyed farms demonstrates that *C. africana* plays a significant role in the farming systems. Such adoption indicates that farmers understand this tree species may offer them some advantages in their agroforestry enterprise.

Figure 2 shows the spatial distribution of nitrogen, phosphorus, potassium, calcium, and carbon under the canopy of C. africana.

Figure 2: Spatial distribution of soil nutrient contents under Cordia africana *canopy*



Results show a trend of soil nutrient content from the base of the tree trunk to the distance of 30M for most of the parameters measured. The nitrogen content of soils was higher at 5M from the tree trunk at 0.253% and decreased to 0.220% at 11M from the tree trunk (Figure 2a). The increased nitrogen concentration close to the tree trunk may be due to the accumulation of the nitrogen-rich leaf litter and the decomposition of the litter, hence releasing nitrogen into the soil (Octavia et al., 2023; Gindaba et al., 2005).

Organic carbon content showed similar trends with sampling points near the tree base, giving values of 2.264% at 5M compared to 2.150% at 30M from the tree base (Figure 2b). At a distance of 5M from the tree trunk, the soils' phosphorus content was 22.22 ppm, which decreased to 21.67 ppm at 11M from the tree trunk and 22.22 ppm at 30M from the tree trunk (Figure 2c). The capacity of the tree to collect phosphorus from deeper soil layers and move it to the surface by leaf litter decomposition is probably responsible for the greater phosphorus level close to the tree base (Odeny, 2016). Soil potassium level ranged from 0.210% at 5M from the tree trunk to 0.470% at 11M and 0.407% at 30M (Figure 2d). Variations in potassium content with distance from the base of the tree may be impacted by soil texture, drainage, and the patterns of potassium absorption and redistribution of the tree (Nair et al., 2021). Calcium levels in the soil ranged from 3.603% at 5M from the base of the tree to 3.157% at 11M and declined to 2.510% at 30M (Figure 2e).

The observed changes in soil nutrient concentration with distance from the *Cordia africana* tree base emphasise the potential of this tree species to promote soil fertility in agroforestry systems. Particularly, nitrogen, phosphorus, potassium, calcium, and organic carbon can be enriched in the soil by the build-up of nutrient-rich leaf litter close to the tree stem and its breakdown. These findings imply that adding *Cordia africana* into agroforestry systems can effectively boost soil fertility and support sustainable agriculture practices in the research area.

Soil Nutrients at Different Soil Depths under *Cordia africana* Canopy

Stratification of soil nutrients at different soil depths under *Cordia africana* canopy is shown in Table 2.

Table 2: Soil nutrients at different soil depths under Cordia africana canopy

Nutrient	Depth (cm)	Mean	Std. Deviation
Nitrogen (%)	0-15	0.248	4.0702
	15-30	0.208	0.0331
Phosphorus (ppmP)	0-15	22.360	4.1751
	15-30	21.296	4.2312
Potassium (%)	0-15	0.308	0.1962
	15-30	0.287	0.2031
Calcium (%)	0-15	3.179	0.8869
	15-30	2.476	0.7668
Magnesium (%)	0-15	3.179	0.8869
	15-30	2.476	0.7668
Organic Carbon (%)	0-15	2.333	0.5420
	15-30	2.042	0.3289

Different patterns were observed in soil nutrients under the *Cordia africana* canopy for each nutrient parameter examined. Findings show a clear trend of high nutrient levels in the topsoil (0-15cm) compared to subsoil (15-30cm) for all soil nutrients. Total nitrogen values were higher at the topsoil at 0.248%, while the subsoil had 0.208%. The results agree with those of Mafongoya & Nair (1996), who reported higher nitrogen levels in the topsoils under agroforestry systems in Zimbabwe. The nitrogen content in the upper soil layer (0-15 cm) showed a high variation, with a mean of 0.248% and a standard deviation of 4.0702. This variability can be attributed to leaf litter distribution, root exudates, nitrogen-fixing microorganisms, soil moisture, and possible sampling or measurement errors. In contrast, the nitrogen content in the lower soil layer (15-30 cm) showed less variation, with a mean of 0.208% and a standard deviation of 0.033. The mean total phosphorus content in the topsoil was 22.36 ppm, which was higher than in the subsoil (21.296 ppm), while potassium content values were 0.308% at the 0-15cm depth compared to the subsoil (0.287%). The mean organic carbon content was higher in the topsoil (2.333%) than in the subsoil (2.042%), indicating a higher organic carbon concentration in the upper soil layer. The means were significantly different at p=0.05 (Table 3). For the macronutrients, the trend was different; the subsoil 15-30cm recorded higher contents when compared to the topsoil. Calcium in the 0-15cm soil layer was 3.179%, significantly lower than the 15-30cm, which had 2.476%. Table 3 presents the ANOVA test results for the soil properties investigated in this study.

Table 3. Analysis of Variance of soil nutrients at different depths

ANOVA		Sum of Squares	Df	Mean Square	F	Sig.
Nitrogen (%)	Between Groups	22.871	1	22.871	1.057	0.319
	Within Groups	346.051	16	21.628		
	Total	368.922	17			
Phosphorus (ppm)	Between Groups	15.420	1	15.420	0.940	0.347
	Within Groups	262.347	16	16.397		
	Total	277.767	17			
Potassium (%)	Between Groups	0.044	1	0.044	0.712	0.411
	Within Groups	0.989	16	0.062		
	Total	1.033	17			
Calcium (%)	Between Groups	2.369	1	2.369	3.267	0.090
	Within Groups	11.603	16	0.725		
	Total	13.971	17			
Organic Carbon (%)	Between Groups	1.275	1	1.275	5.831	0.028*
	Within Groups	3.497	16	0.219		
	Total	4.772	17			

* significance level at p=0.05

The results showed that the mean organic carbon in two layers of soil was significantly different ($p < 0.028$), indicating that the incorporation of *Cordia africana* in agroforestry systems affected the distribution of organic carbon in the soil, with topsoil having a higher amount of organic carbon than the subsoil (15-30cm).

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Soil Nutrient Variations in Agroforestry Systems and Cropped Land

The variability of soil nutrients in agroforestry systems as opposed to cropped land is covered in the following section. Each nutrient component, nitrogen, phosphorus, potassium, organic carbon and calcium, is examined separately using mean values from various depths (0–15 cm and 15–30 cm), as shown in Figure 3. The variation in concentrations of soil nutrients as a function of distance from the base of the *Cordia africana* tree and the cropped land is presented in Figure 3. Total nitrogen, phosphorus, organic carbon, potassium, and calcium show a decreasing trend with increasing distance.

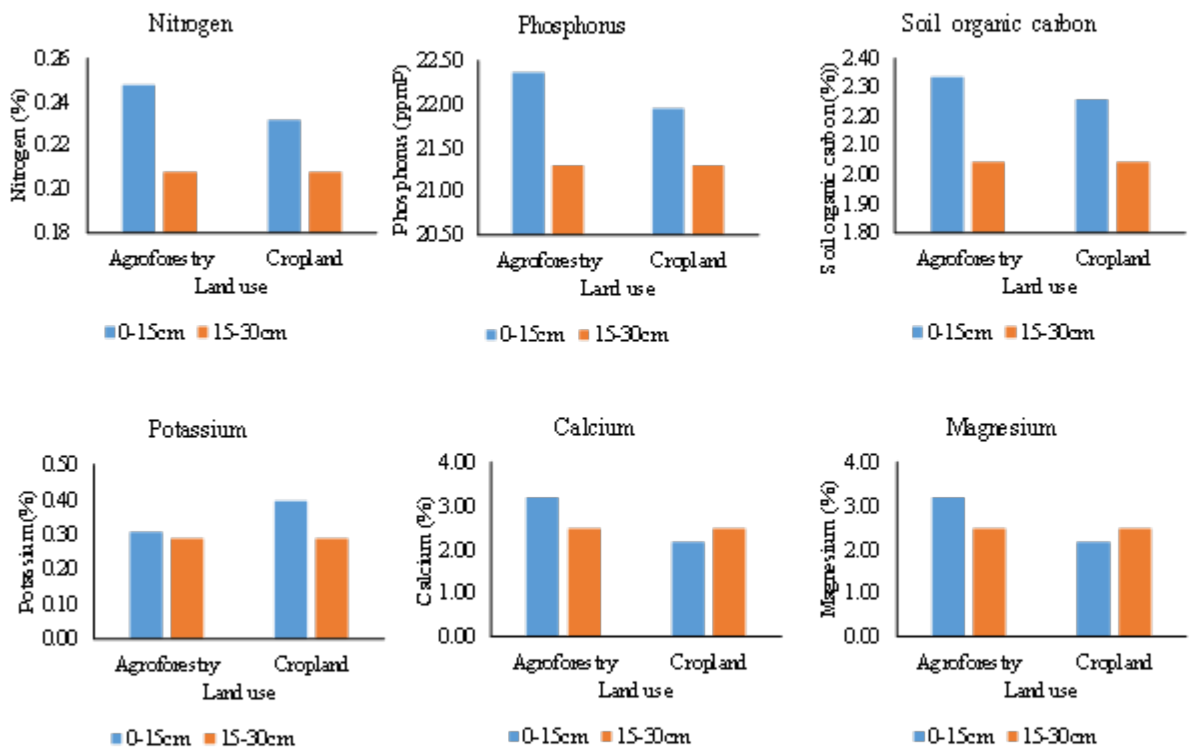

Figure 3: Comparison of soil nutrient availability in agroforestry systems and cropped land

While cropped land exhibits lower values of total nitrogen (0.25%), the topsoil in agroforestry systems has a mean nitrogen level of about 0.26%. In agroforestry systems, the subsoil nitrogen levels are also greater (around 0.22%) than on cropped land (about 0.20%).

Phosphorus levels are significantly higher in agroforestry systems compared to cropped land. The topsoil in agroforestry systems contains around 23.0 ppm of total phosphorus, while cropped land has approximately 22.00 ppm. The subsoil phosphorus content in agroforestry systems was 21.50 ppm, compared to 21.00 ppm in cropped land. Topsoil potassium levels in agroforestry systems are 0.45%, although in cropped land, they are higher at (0.40%). The topsoil in agroforestry systems has an organic carbon content of 2.6%, compared to 2.5% in cropped land. The subsoil organic carbon in agroforestry systems was 2.25%, while cropped land shows a lower value of approximately 2.0%.

Cropped land and agroforestry systems differ significantly in soil calcium content. At both soil depths in agroforestry systems, the calcium content is higher on the subsurface (15–30 cm), with a mean of 3.0% compared to the topsoil (0–15 cm), which is about 3.50%. On the other hand, farmed areas had lower calcium levels, with the subsoil at around 2.25% and the topsoil at about 2.75%.

Nutrient Content of *Cordia africana* Leaves

Table 4 shows results for the quality of *Cordia africana* leaves. The nitrogen content of the leaves was 1.75%. Compared to other agroforestry trees like *Grevillea robusta* (1.2%) and *Sesbania sesban* (1.5%), *Cordia africana* leaves have a relatively high nitrogen content (Nyberg & Högberg, 1995), while phosphorus was 0.28%. These findings are similar to those observed by Kassa et al., (2022), who obtained nitrogen levels of 2.01% and 0.89% potassium in southwestern Ethiopia.

Table 4: Nutrient content of Cordia africana leaves

Nutrient	Content (%)
Nitrogen	1.75
Phosphorus	0.28
Potassium	2.67
Calcium	3.27
Magnesium	0.52

The findings in Table 4 support the results by Mahari (2014), who found that the leaves of *Cordia africana* are rich in major plant nutrients nitrogen, phosphorus, and macronutrients calcium and magnesium. The environmental conditions influence the breakdown of litter, the quality of leaf litter as physicochemical properties such as lignin content, tannin and lignin to nitrogen ratio (Negash & Starr, 2021). The results of this study suggested that *Cordia africana*, naturally occurring on farms or planted in agroecosystems, can replenish soil fertility through litter fall.

Spatial Distribution of Soil Nutrient under *Cordia africana* Canopy

The study revealed significant variation in the spatial distribution of soil nutrients under the *Cordia africana* canopy. Trends of soil nutrient content with distance from the *Cordia africana* tree trunk indicate the capability of this tree species to enhance soil fertility in agroforestry systems. Ndlovu (2013) found that integrating *Cordia africana* improves soil nitrogen status and maize production in agricultural systems. Likewise, research conducted by Odeny (2016), found that the availability of potassium and phosphorus in the soils under *Cordia africana* was higher. On the other hand, naturally added *Cordia africana* leaf litter may improve the soil's ability to retain and supply water, improve tilth, and reduce erosion (Sileshi and Mafongoya, 2020; Nair et al., 2021). The accumulation of leaf litter at the tree's base and its subsequent decomposition can enhance the nutrients such as nitrogen, phosphorous, calcium, magnesium and organic carbon (Gota et al., 2024). From the above findings, it can be concluded that intercropping *Cordia africana* into agroforestry practices can be an efficient way to improve soil fertility, thereby supporting sustainable agriculture in the study area.

Soil Nutrients at Different Soil Depths under *Cordia africana* Canopy

This research revealed that soil nutrients were significantly higher in the 0-15 cm layer than in the 15-30 cm layer underneath the *Cordia africana* tree. These high nutrient contents in the agroforestry system can further lead to improved nutrient dynamics due to enhancement factors, increased nutrient supply through biomass returns from trees, and changes in soil physical and biological characteristics brought about by trees (Octavia et al., 2023; Gindaba et al., 2005; Etafa et al., 2023).

Tree-based land use systems are more efficient in maintaining soil fertility than annual cropping systems (Schroth et al., *2001*; Nair et al., 2021). The integration of *Cordia africana* into the farming systems of smallholder farmers in Kirinyaga County, Kenya, should be prioritised for the sustainable improvement of soil fertility and increased production of food crops. In addition, utilisation of this resource will minimise the application of external inputs like chemical fertilisers and encourage the use of environment-friendly and economically viable systems for maintaining soil fertility.

Conclusion

Tree-based solutions are more efficient in the nutrient cycle in farming systems and, hence, ideally suited for impoverished farmers experiencing food insecurity. Agroforestry trees positively affect soil fertility through litter fall and decomposition of organic matter. In addition, their contribution to diverse needs, such as income and nutrition security from high-value fruits, wood for household energy supply, high-quality fodder for livestock, and timber/poles/posts for construction. The soil-improving capacities of trees and their application in agroforestry systems is a major focus of agroforestry. Consequently, comparing agroforestry systems with cropped lands highlighted that the soils under agroforestry management had enhanced stock of organic carbon to the extent useful in enhancing soil structure, water holding capacity and nutrient retention. High nutrient value in agroforestry systems shows *Cordia africana's* ability to implement sustainable agriculture practices. This corresponds to the earlier findings that agroforestry systems, especially those that include *Cordia africana*, can help overcome all the challenges facing the fertility of the soils, thus improving the yields and food security.

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