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Scattered tree species' leaf litter quality and impact on soil properties in enset homegardens of South Ethiopia: a case for conserving old trees

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Enset (*Ensete ventricosum*) is among the under-researched African crops that serve as a staple food crop in South Ethiopia. Despite potential benefits, tree species are rarely integrated into enset farms, and their potential to enhance soil fertility in enset systems remains largely unexplored. As a consequence, reliable recommendations for farmers are lacking. This study aimed to evaluate the influence of dominant tree species on soil physicochemical properties in enset-producing homegardens in the Gamo Highlands of South Ethiopia. Under the five most common tree species, we measured 11 soil health indicators and compared them at three radial distances from tree trunks. Those results were compared to the elemental composition of the tree leaves and their decomposability. In on-farm observations, soil physicochemical properties varied widely between farms, yet significant intra-farm differences were observed only in TN, Pav, K, Ca, Mg, and cation exchange capacity. Tree species identity and radial distance had no significant effect on most soil physicochemical properties; however, their interaction significantly influenced TC, C/N ratio, Ca, and CEC, with the highest values observed beneath canopies of larger, older *Ficus sur* trees. Nevertheless, leaf litter elemental composition differed significantly among tree species. *Croton macrostachyus* had the lowest C/N ratio and the highest nutrient concentrations, while *Cordia africana* decomposed at a slower rate. Overall, our field observations suggest that large, old trees can contribute to maintaining soil fertility and therefore should be conserved as much as possible within enset farming systems. The potential of planting new trees to replenish soil nutrients will, thus, depend on the consistency of the measure, the density of trees, and the leaf biomass to be incorporated over time. Furthermore, given the wide variation in litter properties among species, recommendations to farmers should match tree characteristics to specific soil conditions and amendments to best enhance fertility based on their needs.

KEYWORDS

Ensete ventricosum, homegarden, litter quality, soil health, tree species

1 Introduction

The prevalence of food insecurity in Africa remains nearly twice the global average (FAO, IFAD, UNICEF, WFP, and WHO, 2024). Regional food crops that play a significant role in local diets are a promising avenue to address this situation, but they have received limited policy support and research attention (FAO, 2024). One such crop is enset (*Ensete ventricosum* (Welw.) Cheesman) (African Orphan Crops Consortium, 2013; National Research Council, 2006), which, despite its expanding cultivation area (Tsegaye and Struik, 2001; Chase et al., 2023) and serving a large number of people as a staple (Borrell et al., 2020), remains among the least studied crops in Africa (African Orphan Crops Consortium, 2013; Borrell et al., 2019; National Research Council, 2006). It is a perennial multipurpose crop resembling a banana, cultivated exclusively in Ethiopia, where it provides food, fiber, animal forage, construction materials, and traditional medicine (Borrell et al., 2019; Brandt et al., 1997). In South Ethiopia, enset forms the backbone of subsistence agriculture, with its drought tolerance, high biomass production, flexible harvesting time, diverse products, and long-term product storage in a traditional setting being a major asset in local food security (Birmeta et al., 2004; Borrell et al., 2020; Chase et al., 2023; Yemata, 2020). Moreover, its suitable agro-ecological range can extend beyond its current cultivation range to other parts of South and East Africa, suggesting significant potential to support more communities than it presently does, if supported by climate-smart and sustainable production strategies (Belay et al., 2017; Koch et al., 2021). However, some enset-growing areas are increasingly affected by land degradation, such as erosion and landslides, which threaten the long-term viability of livelihoods (Getahun et al., 2025; Shano et al., 2021).

There is a strong body of literature indicating that cropping systems with a mixed, multilayered approach, such as agroforestry, can increase food production resilience while simultaneously curbing land and soil degradation (Charles et al., 2013; Fernandes et al., 1985; Hemp, 2006; Ssebulime et al., 2019; Zake et al., 2015). In agroforestry systems, trees can contribute to soil fertility by returning nutrients to the surface through nitrogen fixation, litterfall, or pumping up nutrients from deeper soil layers inaccessible to the roots of herbaceous crops (Akinifesi et al., 2010; Garrity et al., 2010; Sileshi et al., 2008; Solanki et al., 2024). Additionally, tree litterfall can increase soil carbon stocks (Negash and Starr, 2021; Solanki et al., 2024). These processes enhance soil health and plant production by improving nutrient cycling, soil organic matter (SOM) accumulation, soil biological activity, and soil charge characteristics (Mehari and Abera, 2019; Merckx et al., 2001; Palm et al., 2001). Additionally, agroforestry systems have also been shown to offer climate change adaptation benefits by buffering intense solar radiation and regulating microclimatic conditions (Nair et al., 2022).

In Ethiopia, the benefits of agroforestry are highly relevant, as annual aggregate yield losses due to erosion and soil nutrient decline are estimated to exceed 100 million tons, and the country is at high risk of yield losses due to increasing temperature extremes (Tilahun, 2021). A fatal landslide in 2024, which occurred in Southern Ethiopia and killed more than 250 people (Shano et al., 2024), further underscores the urgency of curbing the high deforestation rates observed in the Ethiopian rift in recent decades. For enset, however, agroforestry is practiced only in a few parts of south Ethiopia, such as in Gedeo and Sidama, where it is grown beneath a canopy of trees and a gap between overstory trees (Abebe et al., 2006; Abebe and Bongers, 2012; Borrell

et al., 2020; Negash and Starr, 2013). Across much of its cultivation area, enset is grown as a monocrop and soil amendment in homegardens mainly relying on manure and household waste. Such dependence on livestock-derived inputs poses overgrazing strains on the already degraded tropical soils (Amede and Taboge, 2007; Assefa and Bork, 2017; Shara et al., 2021; Tamire and Argaw, 2015; Tsegaye and Struik, 2002). In certain locations, particularly in the Gamo highlands, previous studies have reported nutrient imbalances in enset-producing areas (Shara et al., 2021), largely linked to the absence of optimized nutrient recommendations and the unregulated application of cow manure. Farmers commonly allow manure to flow directly onto enset farms situated around homesteads (Own Obs.; Garo et al., 2022; Shara et al., 2021). In the location, enset is primarily grown as a monocrop, with trees integrated into only a few homegardens (Bireda et al., 2026). Given the sloping terrain and the high moisture content of manure, which makes transport difficult, this practice has been considered the most practical option (Own Obs.). Consequently, this practice tends to overfertilize enset plants near the homestead while leaving those in the outfields underfertilized (Shara et al., 2021). Although enset is well recognized for its substantial contribution to soil and water conservation, its relatively shallow rooting depth limits its capacity to reinforce deeper soil layers and regulate subsurface water movement and casual landslides (Senbeta et al., 2022; Zewdie et al., 2008). Therefore, in volcanic landscapes characterized by steep slopes and deeply incised valleys and gullies, such as the Gamo highlands in Ethiopia (Coltorti et al., 2019), the stabilizing effect of deep-rooted trees on perched water tables and slope dynamics is highly important.

However, the potential ecological benefits of integrating trees in enset-based homegarden systems remain underexploited. One of the major reasons for this is that farmers have scarce land, and leaving space for trees is not well evidenced (Own Obs.). As a result, in the Gamo highlands, trees are only sparsely incorporated into the enset farming system (Bireda et al., 2026) and are largely confined to traditional protected areas, such as burial grounds, mystical sites, and woodlands (Massa and Mosa, 2021), or found along roadsides and the outer rims of gardens. The scattered trees present within enset gardens help reduce higher temperatures, enhance soil moisture, and the understory enset plants exhibit the phenotypic plasticity required to adapt to the shading imposed by these trees (Bireda et al., 2026). This buffering is particularly important because enset is highly susceptible to stressors such as frost and heat (Amede and Taboge, 2007; Shara et al., 2021), which suppresses growth and increases vulnerability to diseases (Meta et al., 2022). Despite this, very few studies have examined the potential role of these trees in enhancing soil function in the Ethiopian Rift.

A comprehensive understanding of the impact of specific agroforestry species on soil functioning is essential for making informed management recommendations (Negash and Starr, 2021). In general, tree traits vary considerably among species, and species identity plays an important role in regulating litter decomposition and nutrient release (Bekele and Gebremedhin, 2024; Getaneh et al., 2022). This variation is associated with differences in litter chemical composition, including nutrient concentrations and structural compounds such as lignin and phenol (Getaneh et al., 2022; Patoine et al., 2020; Peng et al., 2022a). In addition to litter quality, tree species can indirectly influence decomposition processes by modifying microclimate conditions, such as soil moisture and temperature and affecting soil biotic activity (Anbessa and Utaile, 2024; Peng et al., 2022b; Sari et al., 2022; Trofymow et al., 2002). However, agroforestry tree species may also create tradeoffs through

competition with understory crops for nutrients (Bertsch-Hoermann et al., 2021; Gonçalves et al., 2021). Despite increasing research, information remains limited for many agroforestry tree species.

In particular, only a limited number of investigations have assessed the potential of tree species in our study region to maintain soil fertility (Anbessa and Utaile, 2024; Bekele and Gebremedhin, 2024; Getaneh et al., 2022; Gindaba et al., 2004; Kassa et al., 2022; Negash and Starr, 2021; Teklay and Malmer, 2004). Moreover, the enset agrosystem in Southern Ethiopia lies within the Rift Valley, where the soil varies markedly across the production range, and its management practices differ from those of other cropping systems included in previous studies. These sources of variability underscore the need for additional data to establish local reference ranges and provide context-specific guidance for farmers and policymakers (Amede and Taboge, 2007; Kudama et al., 2022; Shara et al., 2021). Therefore, this study aims to evaluate the influence of common tree species on soil physicochemical properties in enset-based homegardens of the Gamo highlands of South Ethiopia. In addition, we assessed the tree species' litter elemental composition and decomposability to evaluate how these may contribute to soil fertility differences in the enset systems. We hypothesize that tree species vary in their litter quality and, therefore, their influence on soil physicochemical properties in enset farms.

2 Methodology

2.1 Description of the study area

The study was conducted in the enset-producing catchment of the Gamo Highlands of Ethiopia (Chencha, Geresse, and Kamba

woredas), at an elevation ranging from 2,100 to 3,000 m a.s.l. The mean annual temperature ranges between 23 °C in the lowlands and 14 °C in the highlands; the mean annual rainfall is between 750 mm and 1,700 mm (Berhanu et al., 2013; Coltorti et al., 2019). The landscape has been severely deforested and is now predominantly covered by annual crops (Assefa and Bork, 2014, 2016), while forest trees and other perennials cover a small percentage of the land use (Amejo et al., 2019). The dominant soil types are Nitisols and Luvisols (IUSS Working Group WRB, 2022).

2.2 Sampling plot/tree selection

From a reconnaissance survey of more than 150 enset homegardens, 38 farms with solitary trees (Figures 1, 2B) were selected with the criteria of the availability of the tree species of our interest and suitability for the sampling setup to evaluate tree influence on soil properties in enset homegardens and evaluate leaf litter quality. The selected trees were at least 10 meters away from the nearest woody plants, and the direction towards the houses was omitted from sampling (Figure 3A), as it is reported to be often overfertilized with manure (Shara et al., 2021). Each tree species was represented by eight replications (eight farms), except *C. macrostachyus*, which was represented by six farms due to the limited availability of farms suitable for the experimental setup.

2.3 Tree leaf collection and soil sampling

Scattered tree species in enset-based homegardens of the Gamo highlands of southern Ethiopia were used as described in our previous work (Bireda et al., 2026). Five native tree species, namely *Cordia africana*, *Erythrina brucei*, *Ficus sur*, *Hagenia abyssinica*, and *Croton macrostachyus*, the most commonly found inside enset farms, were



FIGURE 1

A typical enset farm in the mountainous Gamo highlands of south Ethiopia, with a tree at the farm border.

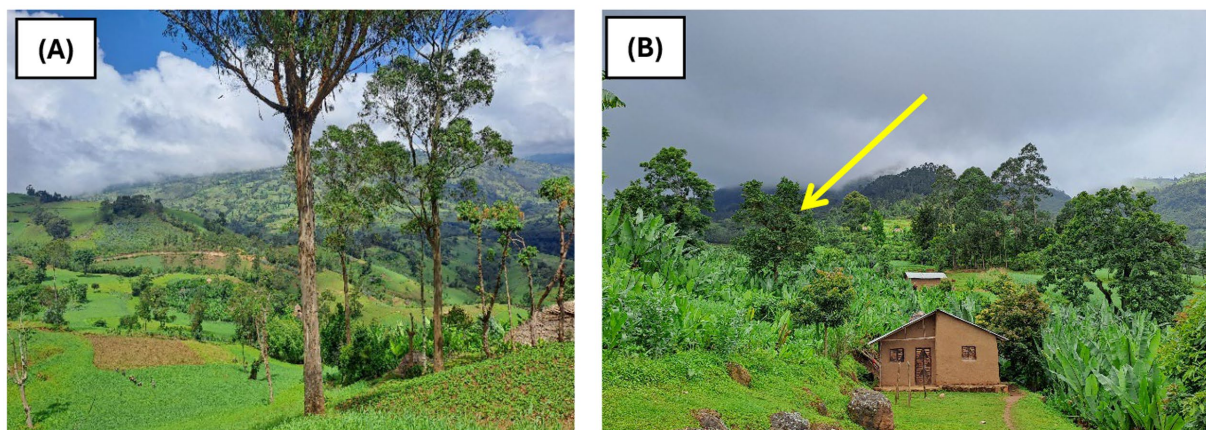


FIGURE 2

Agricultural landscape with annuals and perennials (A) and anset homegarden with sparsely planted trees (B) in the Gamo highlands of south Ethiopia. The arrow in panel B indicates a tree located within the anset plot, while other trees are situated at the farm's border.

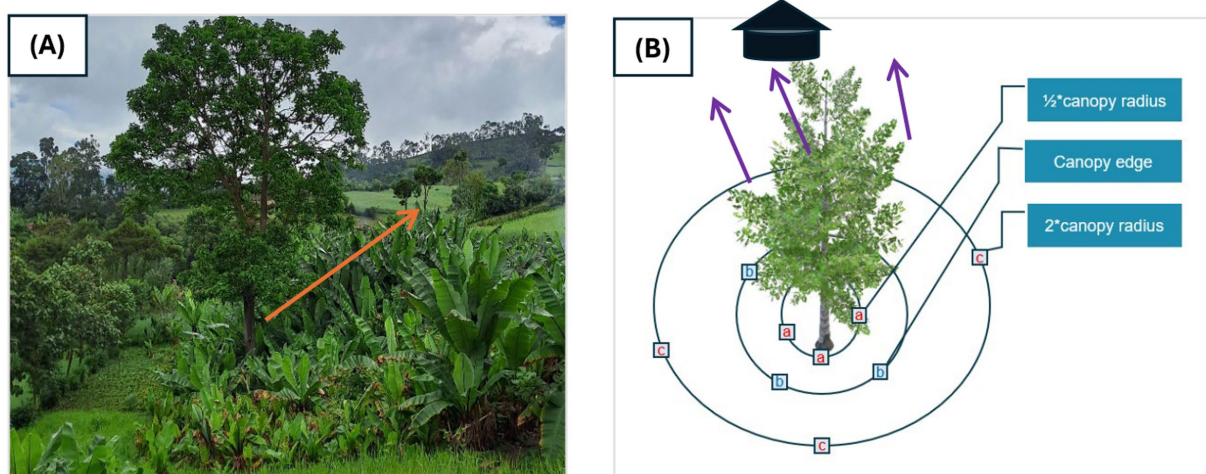


FIGURE 3

Anset farm with a solitary tree (A) and soil sampling scheme at three distances from the tree trunk (B). Soil was sampled in the middle of the canopy (a), at the edge (b), and outside the canopy (c). Teabag plots were established in the middle (a) and outside (c) of the tree canopy for 4 months on a single farm (October 2024 to February 2025). Arrows indicate direction toward the houses, which were excluded from sampling to avoid a potential bias of overfertilization.

selected for this study. Leaf samples were collected from the five tree species solitarily grown in 38 anset homegardens, totaling 38 leaf samples. Mature leaves were handpicked from accessible branches located at the mid-canopy position and allowed to dry at room temperature. Under each tree, three circular plots (in the middle, at the edge, and at a distance twice the tree canopy radius) were laid out (Figure 3B). Soil samples were taken from three sampling points per radius at a depth of 0–30 cm, a common hoeing depth and where most of the anset root cords are distributed (Zewdie et al., 2008), using an auger. Then, the three soil samples at each distance were pooled into one composite sample, resulting in a total of 114 soil samples.

2.4 Litter decomposition experimental setup

For the litter decomposition experiment, after air drying of the collected leaf litter (section 2.2), 2 g of ground litter from each of the five tree species was transferred into empty nylon mesh tea bags and

sealed with a plastic sealer following the method described by Getaneh et al. (2022). Lipton Green (EAN: 87 22700 05552 5) and rooibos teas (EAN: 87 22700 18843 8), hereafter referred to as Green tea and Red tea, respectively, were included as reference materials for decomposition rate comparison, following Keuskamp et al. (2013). Leaf litter of the five tree species and the two standard teas hereafter are referred to as 'litter type' for the decomposition experiment. The litter bags were oven-dried at 70 °C for 24 h, and the initial weight was recorded before establishment in the field plots. A single *H. abyssinica* tree, planted inside an anset farm, was used as the experimental site to simulate the microclimate under and outside the tree canopy. Plots were set up following Getaneh et al. (2022) with some modifications to accommodate the tree canopy cover effect. Six random 3 m x 3 m plots (three under the canopy and three at a distance twice the canopy radius) were established, where eight litterbags per litter type (two bags to be retrieved each month for 4 months) were installed at 20 cm intervals and approximately 8 cm depth (Figure 3). Each litter was replicated six times, which resulted in 336 litter bags of five commonly

planted trees in enset farms and of Green tea and Red tea as fast and slow-decomposing references, respectively.

2.5 Laboratory analysis

The leaf litter and soil samples were moved to the Arba Minch University laboratory and air-dried at room temperature until fully dried. The soil samples were ground and sieved using a 2-mm sieve for further elemental analysis. The soil texture was measured using the Bouyoucos hydrometer method (Bouyoucos, 1962). Soil pH and electrical conductivity (EC) were measured following the standard operating procedures of GLOSOLAN, using a 1:2.5 and 1:5 soil-to-water ratio, respectively. The EC was then converted into Ece (the EC of the saturated soil paste) using the relationship: $E_{ce} = 5.37 EC_{1.5} + 0.57$ (Khorsandi and Yazdi, 2011). The amount of available P was measured using a spectrophotometer, after extraction using the Bray-II method with the extracting solution of 0.03 M NH_4F + 0.1 M HCl, following the GLOSOLAN standard procedure (Bray and Kurtz, 1945; FAO, 2021). Soil TC and TN were measured by total combustion using a CN elemental analyzer (FLASH 2000) (Gordon and Sutcliffe, 1973). Finally, the CEC and the exchangeable bases were analyzed using the Cobalt(III) hexamine chloride (COHEx) method (Nel et al., 2023).

Similarly, the dried leaves were ground and sieved with a 2 mm sieve for elemental composition analysis and the decomposition experiment. Litter total carbon (TC) and total nitrogen (TN) were analyzed following the same procedure as the soil, while the concentration of P, K, Mg, Ca, Na, S, Zn, Cu, Fe, B, Mn, and Al were analyzed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; Thermo Scientific iCAP 7,400 Duo) (Charles and Fredeen, 1997; Helser et al., 2022).

For a decomposability test (tea bag experiment), twelve litter bags (six from under the canopy and six from outside the canopy) of each litter type were retrieved from the field monthly for 4 months. This resulted in a total of 84 litter bags collected each month (7 litter types $\times$ 2 canopy cover $\times$ 6 replication). Adhered soil was manually removed from the litter bags using a brush. The litter bags were then oven-dried for 24 h at 70 °C and weighed with a 0.01-g precision electronic balance. The percentage of the remaining mass was calculated using the initial and final weights of the same litter bag.

2.6 Data analysis

All statistical analyses were performed using R software version 4.3.3 (R Core Team, 2024). First, the elemental composition of leaf litter was analyzed using a linear model (LM), with litter type (tree species) as the main predictor and tree age as a covariate. This was followed by pairwise comparisons between species using the Tukey correction. Second, a linear mixed model (LMM) was fitted with tree species, radial distance (middle, edge, and twice the tree canopy radius), and their interaction as fixed factors and individual farms as a random factor to evaluate the effect of tree species on soil properties. The models were fitted with the *lmer* function from the *lme4* R package (Bates et al., 2015). A Shapiro–Wilk test and a normal quantile plot were used to assess normality. Data were log-transformed for EC, P_{av} , TC, Ca, Mg, K, and Na. Marginal and conditional R^2 coefficients (R^2_m/R^2_c) were calculated for each final model using the *MuMIn* function in the *MuMIn* R package. Then, Cohen's f^2 was quantified using the *effectsize* R package to measure effect sizes of the fixed factors (Cohen, 2013; Selya et al., 2012). Multiple

comparisons were performed with Tukey's *post hoc* test using the *emmeans* function in the *emmeans* R package. Additionally, offsets of the soil variables were calculated as the difference between the values at the middle of the canopy and those outside the canopy to visualize the effects of tree species. Third, a linear model was constructed to evaluate the remaining litter mass (i.e., decomposition rate) as a function of litter type (five tree species, Green tea, and Red tea), canopy cover (beneath vs. outside the canopy), incubation period (1, 2, 3, and 4 months), and all first-order interactions. Finally, an LM was fitted using only the data from the fourth month, with remaining litter mass as the response variable and litter type, canopy cover, and their interaction as predictors. A Spearman rank correlation analysis was then performed to assess the relationship between mass remaining (decomposition rate) and the initial elemental composition of leaf litter across the tree species. The results were visualized using the *ggplot2* and *ggpubr* functions in R software.

3 Results

3.1 Soil properties in enset homegardens

The soil properties for each farm are summarized in [Supplementary Table S1](#). The soil bulk density was relatively consistent across farms, ranging from 0.78 to 1.18 g/cm³. The Ece and pH ranged from 0.73–1.67 dS/m and 5.3–6.9, respectively. Notably, greater variability in P_{av} , base cations, CEC, and base saturation was found between farms. Mean soil properties outside overstory tree canopies at a distance twice the canopy radius are presented in [Table 1](#) to characterize baseline soil conditions across the study area. The analysis results showed clearer elevation-related patterns for several soil chemical properties, while some remained stable ([Supplementary Table S2](#)).

3.2 Tree species' effects on soil properties

The LMM analysis results revealed that most soil properties were not significantly influenced by tree species, radial distances, or their interaction ([Table 2](#)). There were no significant differences in bulk density, electrical conductivity, pH, TN, P_{av} , exchangeable cations (K, Mg, and Na), and base saturation. However, significant interaction effects of tree species and radial distances were observed for TC ($p < 0.05$), C/N ratio ($p < 0.01$), Ca ($p < 0.05$), and CEC ($p < 0.05$) ([Table 2](#)). The mean separation analysis showed that these interactions were observed only with *F. sur*. The higher TC (5.1%), C/N ratio (10:1), Ca (3,444 mg/kg), and CEC (18.9 cmol/kg) were recorded in the middle of the canopy of *F. sur* compared to the edge and outside the canopy ([Supplementary Figure S1](#)). Conversely, the lower TC (4%), C/N ratio (8.8:1), Ca (2,558 mg/kg), and CEC (23.7 cmol/kg) were recorded outside the canopy. The TC and C/N ratio in the middle of the canopy of *F. sur* were not statistically different from those at the canopy edge. However, Ca and CEC in the middle of the canopy of *F. sur* were significantly higher than those at the canopy edge and outside the canopy. The analysis of tree species effects on soil property offsets also showed that TC, C/N ratio, CEC, and Ca were higher under *F. sur* compared to the open area (outside the canopy) ([Supplementary Table S2](#); [Supplementary Figure S1](#)).

TABLE 1 Soil properties outside overstory tree canopies in enset homegardens of the Gamo highlands of southern Ethiopia.

Elevation	BD (g/cm ³)	EC (dS/m)	pH	Pav (mg/kg)	TC (%)	TN (%)	CN ratio	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	Na (mg/kg)	CEC (cmolc/kg)	BS (%)
Higher (>2,600 m.asl)	0.98 ± 0.15	1.0 ± 0.2	5.9 ± 0.5	15.6 ± 14.8	3.69 ± 1.5	0.4 ± 0.1	9.04 ± 1.6	2832.2 ± 668.9	668.92 ± 186.3	470.58 ± 552.6	17.44 ± 21.5	25.66 ± 6.9	81.94 ± 7.7
Middle (2,300–2,600 m.asl)	1.04 ± 0.06	1.04 ± 0.3	5.98 ± 0.6	22.5 ± 24.8	3.44 ± 1.2	0.4 ± 0.1	8.69 ± 1.6	2682.3 ± 1505.6	550.55 ± 246.3	423.17 ± 458.8	9.67 ± 8.9	22.2 ± 10.9	84.34 ± 11.3
Lower (<2,300 m.asl)	1.01 ± 0.08	1.15 ± 0.4	6.19 ± 0.6	32.95 ± 31.2	3.37 ± 0.7	0.39 ± 0.1	8.57 ± 0.9	3331.81 ± 1765.5	860.24 ± 422.9	596.78 ± 491.9	9.26 ± 10.9	29.57 ± 13.8	84.06 ± 9.2

Values are given as mean ± SD and clustered by elevation range where farms were selected (<2,300, 2,300–2,600, >2,600 m.asl).

3.3 Leaf litter elemental composition of trees

There was no significant difference in the total C content of the five tree species, which ranged from 41.5% in *C. africana* to 47.0% in *F. sur* (Table 3). In contrast, a significant difference was observed in the C/N ratio, as well as in most macro- and micronutrients (Table 3). Leaf N was highest in *C. macrostachyus* (4.5%) and lowest in *F. sur* (2.8%), resulting in a wide range of C/N ratios, from 9.3 in *C. macrostachyus* to 16.7 in *F. sur*. *C. macrostachyus* also had significantly higher leaf P (5,268 mg/kg) and K (28,936 mg/kg) compared to the other species. Leaf Ca content was highest in *F. sur* (17,004 mg/kg) and *C. africana* (16,701 mg/kg), whereas *H. abyssinica* had the lowest (9,061 mg/kg). Leaf S was highest in *C. macrostachyus* (2,340 mg/kg) and lowest in *F. sur* (1,154 mg/kg).

3.4 Tree leaf litter decomposability: the effect of litter type and microenvironment

Litter decomposition rate was significantly affected by litter type ($F = 607.9$, $p < 0.001$), presence/absence of overstory canopy cover ($F = 19.3$, $p < 0.001$), and incubation period ($F = 168.5$, $p < 0.001$) (Table 4). It was also significantly affected by the interaction between litter type and incubation period ($F = 4.5$, $p < 0.001$) and marginally by the interaction between canopy cover and incubation period ($F = 2.6$, $p < 0.05$). However, the interaction effect of litter type and canopy cover on litter decomposition rate was not significant ($F = 1.7$, $p = 0.11$). The litter mass remaining during the first observational period ranged from 84.6 to 49.6% (Figure 4A). The rate of mass loss was faster in the first 2 months and slower later in the incubation periods (Supplementary Table S4; Figure 4A). Among the five tree species, *C. macrostachyus* showed the fastest mass loss (Figure 4A), comparable to that of standard Green tea, while the decomposition rate of *C. africana* was as slow as the slowly decomposing Red tea (Figure 4A). *H. abyssinica*, *F. sur*, and *E. brucei* showed intermediate decomposition rates compared to the standard Green and Red teas. The mass loss was higher outside the overstory tree canopy compared to beneath the canopy, and it was progressive over time (Figures 4A,B).

Based on the remaining mass after 4 months only, the LM showed that the litter decomposition rate was significantly influenced by both litter types ($F = 143.4$, $p < 0.001$) and overstory canopy cover ($F = 16.9$, $p < 0.001$); however, there was no significant interaction effect ($F = 1.2$, $p = 0.33$) (Table 5). The greatest mass loss occurred in *C. macrostachyus*, comparable to standard Green tea (Figure 5A). Conversely, the least mass loss was recorded for *C. africana*, which decomposed at the same rate as that of the slowly decomposing standard Red tea (Figure 5A). At the end of the fourth-month incubation, the remaining mass was 43.1% for *C. macrostachyus*, 53% for *F. sur*, 56.4% for *E. brucei*, 50.2% for *H. abyssinica*, and 70.4% for *C. africana*. Considering the effect of overstory tree canopy cover on remaining litter mass, the highest loss occurred outside the canopy (open area) compared to under canopy cover (Figure 5B).

Spearman's rank correlation analysis showed a relationship between leaf elemental composition and mass remaining at both the first and last months of decomposition (Supplementary Table S4). At 1 month of incubation, litter P ($\rho = -0.80$), N ($\rho = -0.67$), and Fe ($\rho = -0.60$) exhibited strong negative correlations with the remaining mass. Elements with moderate negative correlations included S ($\rho = -0.50$), K

TABLE 2 Effects of tree species, radial distance (middle, edge, and outside canopy), and their interaction on soil properties inferred by a linear mixed model with farm included as a random factor ($n = 114$).

Fixed factor	DF	DenDF	Soil parameters	p value	R^2m/R^2c	Cohen's f^2	Soil parameters	p value	R^2m/R^2c	Cohen's f^2
Tree species	4	33	BD (g/cm ³)	0.18	13.8/53.5	0.20	Kex (mg/kg)	0.09	16.7/67.3	0.27
Radial distance	2	66		0.22		0.05		0.22		0.05
Tree species: Radial distance	8	66		0.6		0.10		0.76		0.07
Tree species	4	33	ECe(dS/m)	0.18	15.8/68.3	0.20	Ca (mg/kg)	0.41	10.9/87.7	0.12
Radial distance	2	66		0.15		0.06		0.88		0.004
Tree species: Radial distance	8	66		0.12		0.20		<0.05		0.30
Tree species	4	33	pH	0.12	15.6/75.8	0.24	Mg (mg/kg)	0.08	19.1/91.7	0.28
Radial distance	2	66		0.84		0.01		0.8		0.007
Tree species: Radial distance	8	66		0.68		0.09		0.17		0.18
Tree species	4	33	TC (%)	0.19	15.5/85.8	0.19	Na (mg/kg)	0.45	9.1/92.6	0.11
Radial distance	2	66		0.21		0.05		0.48		0.02
Tree species: Radial distance	8	66		<0.05		0.28		0.56		0.10
Tree species	4	33	TN (%)	0.45	9.5/82.8	0.11	CEC (cmolc/kg)	0.37	11.3/91.1	0.13
Radial distance	2	66		0.48		0.02		0.53		0.02
Tree species: Radial distance	8	66		0.35		0.14		<0.05		0.28
Tree species	4	33	C/N ratio	0.04	23.0/80.4	0.33	BS (%)	0.09	14.1/51.9	0.26
Radial distance	2	66		0.38		0.03		0.85		0.005
Tree species: Radial distance	8	66		<0.01		0.36		0.89		0.05
Tree species	4	33	Pav (mg/kg)	0.38	10.1/83.5	0.13				
Radial distance	2	66		0.25		0.04				
Tree species: Radial distance	8	66		0.82		0.07				

TABLE 3 Initial TC (%), TN (%), C/N ratio, and other macro and micronutrients (mg/kg) composition of five selected tree leaf litters in homegardens of the Gamo highlands of South Ethiopia.

Tree species	C (%)	N (%)	C/N	P	K	Mg	Ca	S	Na	Cu	Fe	Zn	Mn	B
<i>C. africana</i> (n = 8)	41.5 ^a	3.2 ^{bc}	13.1 ^b	2,624 ^{bc}	17,783 ^b	3,504 ^a	16,701 ^a	1,747 ^b	41.6 ^{ab}	12.8 ^a	183.7 ^{ab}	29.9 ^a	57.9 ^c	32.5 ^{ab}
<i>E. brucei</i> (n = 8)	43.2 ^a	3.7 ^b	11.7 ^{bc}	2,707 ^{bc}	17,281 ^b	3,120 ^a	14,318 ^{ab}	1,761 ^b	62.0 ^a	8.0 ^b	327.5 ^a	21.4 ^a	192.0 ^b	23.6 ^b
<i>F. sur</i> (n = 8)	47.0 ^a	2.8 ^c	16.7 ^a	1,887 ^c	16,332 ^b	2,457 ^a	17,004 ^a	1,154 ^c	23.0 ^b	7.2 ^b	98.1 ^b	21.9 ^a	118.9 ^{bc}	39.5 ^a
<i>H. abyssinica</i> (n = 8)	44.9 ^a	3.2 ^{bc}	14.2 ^{ab}	3,196 ^b	17,507 ^b	2,997 ^a	9,061 ^b	1,194 ^c	30.5 ^b	6.9 ^b	200.8 ^{ab}	28.3 ^a	47.6 ^c	25.5 ^{ab}
<i>C. macrostachyus</i> (n = 6)	42.7 ^a	4.5 ^a	9.3 ^c	5,268 ^a	28,936 ^a	4,037 ^a	12,148 ^{ab}	2,340 ^a	28.3 ^b	8.2 ^{ab}	213.1 ^{ab}	24.8 ^a	528.3 ^a	28.4 ^{ab}

Different letters within the same column indicate significant differences among tree species based on a Tukey HSD *post-hoc* test ($n = 38$).

TABLE 4 F-statistics showing the remaining litter mass of five tree species in onset homegardens of South Ethiopia as a function of litter type, canopy cover, and incubation period, and their interaction.

Factor	numDF	denDF	Cohen's f^2	p-value
Litter type	6	280	13.03	<0.001
Canopy cover	1	280	0.07	<0.001
Incubation period	3	280	1.81	<0.001
Litter type: Canopy cover	6	280	0.04	0.11
Litter type: Incubation period	18	280	0.29	<0.001
Canopy cover: Incubation period	3	280	0.03	0.05

($\rho = -0.40$), Mn ($\rho = -0.40$) and Mg ($\rho = -0.30$). Positive correlations were recorded for Ca ($\rho = 0.80$), C/N ratio ($\rho = 0.50$), B ($\rho = 0.50$), and Cu ($\rho = 0.30$). A similar trend was observed in the following months.

4 Discussion

4.1 The influence of scattered trees on soil properties in onset homegardens

Considerable variation was observed in soil properties among farms, likely arising from differences in management practices and landscape position (Shara et al., 2021). Those located at lower elevations generally exhibited more favorable soil chemical conditions, as evidenced by higher soil pH, greater plant-available phosphorus, elevated exchangeable base cations (Ca, Mg, and K), and higher cation exchange capacity compared with farms situated at middle and higher elevations. Overall, these patterns indicate a consistent decline in soil fertility indicators with increasing elevation, in line with previous findings in the system (Shara et al., 2021). In addition, substantial variability was observed among farms within the same elevation category.

The mixed-effect analysis revealed that the effect of tree species, radial distance, and their interaction was not significant for most soil response variables. The possible explanation is that the highest variance likely emerged from the random factor, as evidenced by the observed high inter-farm variability (Supplementary Table S1). This strong “farm effect” most likely can be attributed to a strong heterogeneity among households in terms of soil fertility management, particularly in manure and household waste application. Not all households have equal access to manure, and a lack of standardized agronomic guidelines for onset cultivation contributes further to large differences in application rates (Amede and Taboge, 2007; Bezabih et

al., 2016; Shara et al., 2021). In addition, the environment (farm location) and parent materials play a significant role in the high inter-farm variability (Elias, 2017; Minda et al., 2018; Shara et al., 2021; Vancampenhout et al., 2006). In addition, situated along the escarpment of the Ethiopian Rift Valley, our study area features gently undulating terrain dissected by steeply profiled rivers and is severely affected by erosion, primarily due to rill and gully formation (Coltorti et al., 2019), which contributes to the inter-farm variability.

The LMM result also revealed that the interaction of species and radial distance had a significant effect on TC, C/N ratio, Ca, and CEC, with effect sizes ranging from moderate to high. Overall, the effect size analysis indicated that tree species identity exerted a relatively greater influence on these soil properties than radial distance, highlighting the important yet moderate contribution of species identity to soil fertility. As presented in Supplementary Figure S1, these variables were higher under the canopies of *F. sur* than under those of the other species studied. This species has been identified in a previous study (Bireda et al., 2026) as the species with typically the oldest individuals, which may contribute to the elevated nutrient levels under the canopy through long-term pumping up of subsoil nutrients (Getachew et al., 2023; Lehmann et al., 1998; Raj et al., 2024). This was also supported by the higher level of Ca in the leaf of *F. sur*. Moreover, leaf litter of *F. sur* decomposed at an intermediate rate, indicating its potential to contribute to organic matter accumulation in the topsoil (Supplementary Figure S1). This accumulation can enhance the soil's CEC by increasing the formation of humic substances that retain exchangeable cations (Lehmann and Kleber, 2015; Malunguza and Devi, 2025; Semwal et al., 2003). In addition, *F. sur* individuals exhibited the largest canopy area among the studied species, thereby reducing temperature extremes within the system (Bireda et al., 2026). This moderated microclimate may promote microbial activity by limiting temperature fluctuations and evaporation, further supporting the stabilization of soil organic matter (Belsky et al., 1993). The extensive canopy also reduces the erosive force of raindrops, ultimately reducing nutrient runoff and leaching while enhancing the retention of base

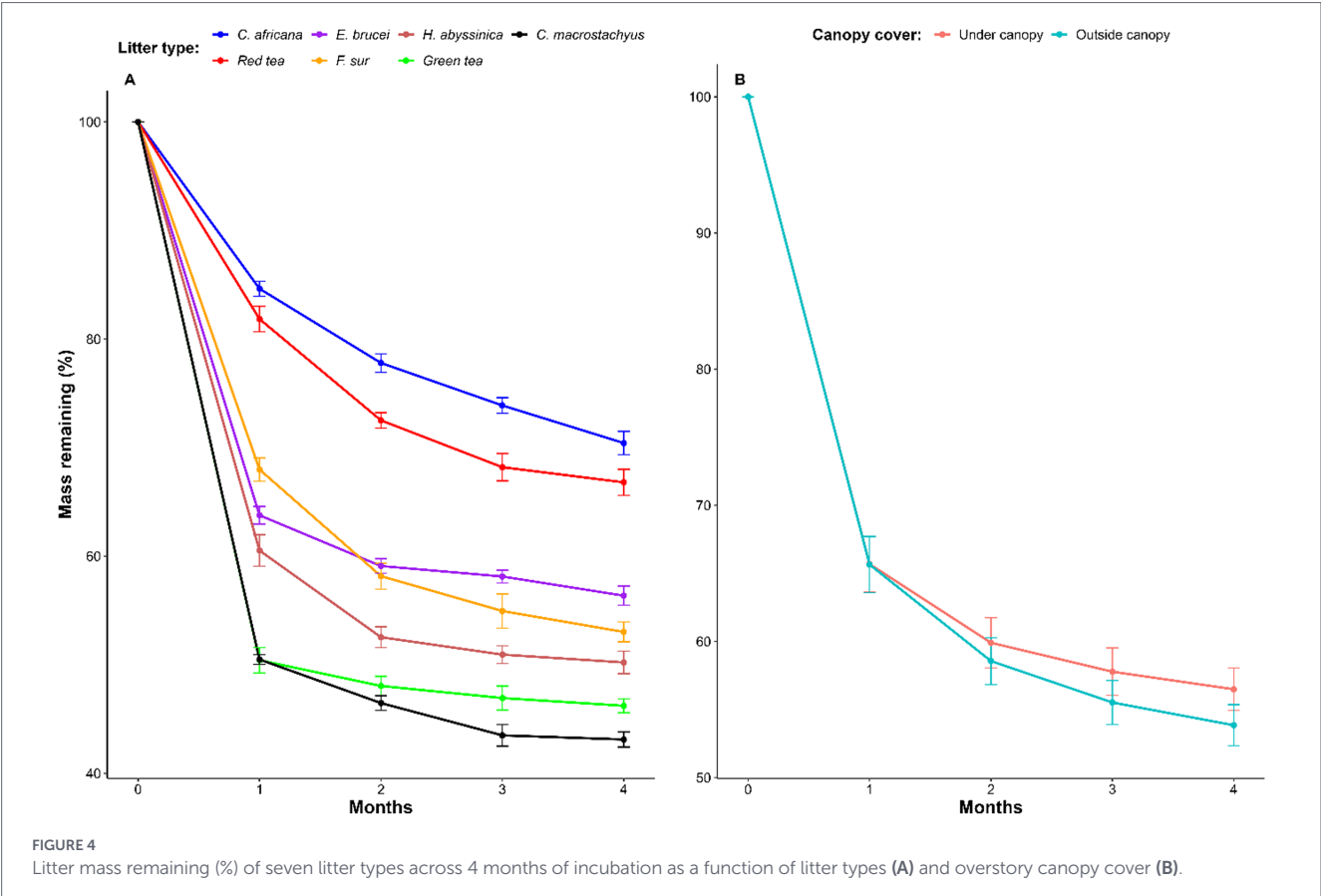


TABLE 5 F-statistics showing litter mass remaining after 4 months of incubation with litter type, canopy cover, and their interaction as predictors.

Factor	DF	Sum Sq	Mean Sq	Cohen's f^2	p-value
Litter type	6	7481.1	1246.8	12.29	<0.001
Canopy cover	1	146.6	146.5	0.24	<0.001
Litter type: Canopy cover	6	61.3	10.2	0.10	0.33

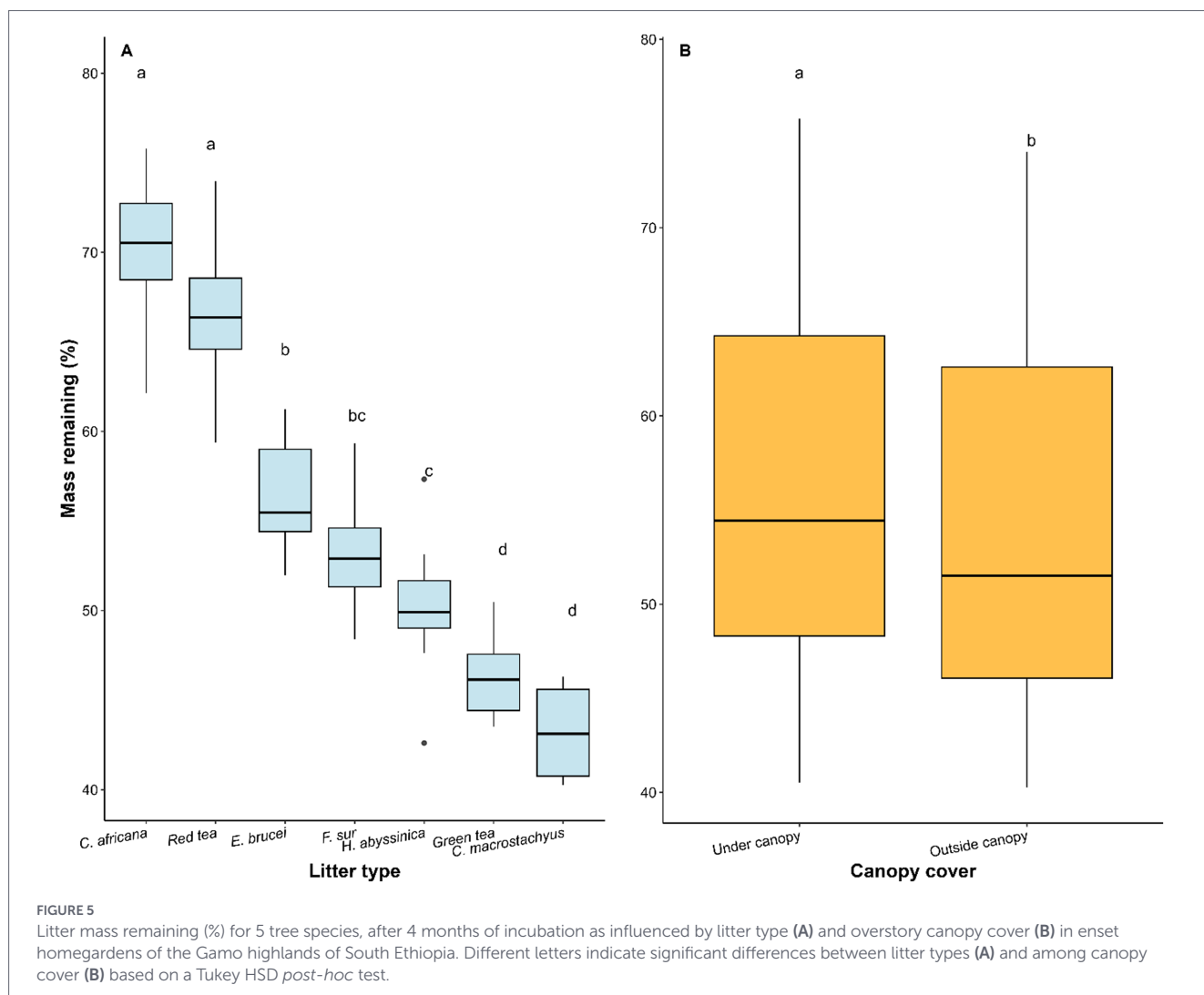
cations such as Ca (Kuyah et al., 2019; Likens et al., 1995). Overall, the offsets by *F. sur* were consistently positive for all variables except BD and P_{av} (Supplementary Figure S1). The effects of tree species on other soil variables were not significant. Contrary to our findings, previous studies in Ethiopia reported that most soil fertility indicators were significantly influenced by species identity (Anbessa and Utaile, 2024; Bazie et al., 2020; Gindaba et al., 2005; Mekonnen et al., 2006). This discrepancy may be because most studies were conducted in annual crop fields, from which substantial nutrients are removed through harvested biomass, and these fields are commonly grown with few or no external inputs. In contrast, in homegardens with perennial enset, nutrients are continuously replenished through manure and household waste, and nutrient removal is minimal because harvesting occurs only occasionally, unlike in annual cropping systems (Sahle et al., 2021; Shara et al., 2021; Tsegaye and Struik, 2001).

4.2 Inherent elemental compositions of leaf litter of common tree species in enset homegardens

Although the general benefits of agroforestry systems are well understood, the Gamo highlands' enset homegardens hardly adopt

such systems. As a result, trees are less likely to be integrated into crop systems and are mainly planted in woodland or roadsides, with few scattered trees in enset farms. We investigated how tree species sparsely integrated into the enset-based farming system of southern Ethiopia influence soil properties and how these effects relate to their inherent litter quality.

Our findings show that the elemental composition of leaf litter varied among tree species. The leaf litter C/N ratio, one of the important indicators of litter quality of tree species, ranged from 9.3 to 16.7, following an ascending order as: *C. macrostachyus*, *E. brucei*, *C. africana*, *H. abyssinica*, and *F. sur*. This difference seemed to originate from a significant variation in litter N content among the species, as the difference in TC was not significant. The leaf N content ranged between 2.8 and 4.5% (equivalent to 28–45 mg/g), comparable to values reported in south Ethiopia (Teklay, 2004) and in the range reported in the organic resource database for the tropics (Giller et al., 2006; Palm et al., 2001). Similarly, the leaf litter P content of all litter types, except *F. sur*, was comparable to the mean values reported for other tree species in the tropics (Giller et al., 2006; Palm et al., 1997, 2001). Among the species studied, *C. macrostachyus* exhibited the highest levels of most nutrients, particularly N, P, K, Mg,



S, and Mn. The Ca, Cu, Fe, B, and Al contents of *C. macrostachyus* were also comparable with the highest values recorded in the other species. This might be due to its fast-growing, resource-acquisitive strategy, characterized by efficient nutrient uptake, short-lived nutrient-rich foliage, and rapid internal nutrient cycling (Orwa et al., 2009; Reich et al., 1997). Our findings align with previous research in Ethiopia. For example, Getaneh et al. (2022) found that *C. macrostachyus* growing in forest remnants of our study area had the highest contents of most nutrients compared to other native and exotic species. Similarly, Negash and Starr (2021) showed that leaf litter from species such as *C. africana*, *C. macrostachyus*, *E. brucei*, *Millettia ferruginea*, *Mangifera indica*, and *Persea americana* differed markedly in chemical characteristics within the agroforestry systems of southern Ethiopia. Additionally, Kassa et al. (2022) reported similar leaf C and N content for *C. africana* and *E. brucei* in homegardens in South Ethiopia. The C/N ratio and base cation content are commonly used as indicators of litter quality (Desie et al., 2020; Reich et al., 2005; Zhang et al., 2008), which can assist tree species selection and nutrient management decisions. In particular, the initial C/N ratio is considered a key factor influencing the decomposability of organic matter and the subsequent nutrient release (Cobo et

al., 2002; Janssen, 1996; Ostrowska and Porębska, 2015). Overall, such organic resources are valuable for increasing nutrient recovery, while their composition, such as N, lignin, and phenol, influences their decomposition and, therefore, application strategies (Giller et al., 2006; Palm et al., 1997, 2001).

4.3 Decomposability of leaf litter of the studied species

Our results showed that decomposition rates were primarily driven by litter type and incubation period, while canopy cover had a minor influence, and the significant litter type $\times$ incubation period interaction indicates that decomposition dynamics vary among litter types over time. Compared to the standards (Keuskamp et al., 2013), as expected, *C. macrostachyus* exhibited the lowest mass remaining throughout the incubation period, with a decomposition rate comparable to that of the rapidly decomposing Green tea. Similar findings have been reported in Ethiopia across cereal fields (Anbessa and Utaile, 2024), grazing land (Gindaba et al., 2004), and forests (Getaneh et al., 2022). *E. brucei*, *F. sur*, and *H. abyssinica* showed intermediate mass loss. In contrast, *C. africana* retained the highest mass, with a

decomposition rate similar to that of the slow-decomposing Red tea. This variation in decomposition rates generally correlated with the initial litter quality. However, exceptions were noted, *C. africana*, which, despite a relatively low C/N ratio, decomposed more slowly over the four-month incubation period than the intermediate-decomposing litter types. This slower rate may be attributed to higher lignin and polyphenol contents (Cobo et al., 2002; Giller et al., 2006; Zhang et al., 2008). This finding aligns with earlier studies in Ethiopia, which reported elevated lignin levels in *C. africana* litter (Mahari, 2014; Teklay and Malmer, 2004). Decomposition was also significantly influenced by canopy cover, although the effect size was smaller than that of litter type. On average, slightly more litter mass remained under the canopy than in the open area. This could be due to reduced solar radiation and limited air circulation beneath the canopy (Mlambo and Mwenje, 2010; Gliksman et al., 2018; Kim et al., 1996), conditions exacerbated by overshading and heavy litterfall under the canopy, as observed in our study. However, as the decomposition experiment was conducted at a single farm level, future studies should include multiple farms across different locations and extend observations over multiple years to capture spatial and temporal variability.

The tree species included in our study are among the most common agroforestry species in Ethiopia. Notably, *C. africana*, *C. macrostachyus*, and *E. brucei* have been reported to produce higher amounts of annual litterfall, largely due to their deciduous nature (Kuria et al., 2017; Negash and Starr, 2013). Furthermore, findings from decomposition and soil respiration studies suggest that litterfall contributions in southern Ethiopian agroforestry systems are sufficient to maintain soil organic carbon levels, thereby sustaining soil fertility (Negash and Starr, 2021). In our study, although most soil variables exhibited a negative offset under the canopy of the trees, except for *F. sur*, it was not significant (Supplementary Figure S1). This suggests that the presence of these trees does not lead to substantial competition for soil nutrients under the current management practices and may be potentially beneficial in the long term. Besides, as observed in our previous study (Bireda et al., 2026), the trees positively impacted microclimate factors, which indirectly reduce the impacts of stressors such as heat and frost. Moreover, these trees could help minimize the loss of essential nutrients from manure by providing nutrient buffering in the system (Gikas et al., 2016; Weigelhofer et al., 2012).

5 Conclusion

This study evaluated how scattered trees of different species affect soil fertility in enset homegardens of the Gamo Highlands in southern Ethiopia. It also examined whether this effect is related to the elemental composition and decomposability of tree leaf litter. Tree species identity significantly influenced soil TC, C/N ratio, Ca, and CEC in enset homegardens, with higher values generally found under large *F. sur* canopies compared to open areas, while other species showed no effect. The *F. sur* trees were typically older, larger specimens, highlighting the importance of

conserving mature trees within farming systems. There was no clear evidence that any of the tree species competed with enset for nutrients, as soil properties under the canopy and open area were not different. The findings also suggest that the leaf litter from these tree species are a high-quality organic resource that can be used directly or mixed with inorganic fertilizers for soil amendment. Therefore, integrating the trees could help maintain soil fertility in the long term and may provide broader ecological benefits, such as buffering extreme climatic conditions and contributing to slope stabilization, which is particularly important in the study area. We suggest a comprehensive future investigation of how these trees affect enset crops' nutrient uptake and biomass production, and potential competition for other resources.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AB: Investigation, Data curation, Writing – original draft, Conceptualization, Visualization, Formal analysis, Methodology. OH: Supervision, Writing – review & editing. ME: Writing – review & editing. BM: Writing – review & editing, Supervision. GG: Conceptualization, Supervision, Writing – review & editing. KV: Supervision, Conceptualization, Writing – review & editing.

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Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1775874/full#supplementary-material>

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