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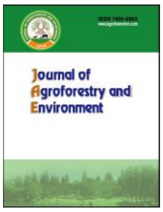

Shade Tree Diversity Modulates Home Field Advantage of Litter Decomposition in Coffee Agroforestry Systems under Phosphorus Fertilization in Southwestern Ethiopia

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Abstract: Shade trees are integral components of coffee agroforestry systems, contributing to microclimate regulation, biodiversity conservation, and nutrient cycling through litter decomposition. This study evaluated home-field advantage (HFA) in leaf litter decomposition under three coffee agroforestry shade systems in Gomma District, southwestern Ethiopia: diverse shade tree species systems, monoculture Albizia (*Albizia gummifera*) shade systems, and unshaded coffee systems. Laboratory incubation experiments were conducted using litter from each shade category under home- and away-field soil conditions, with phosphorus fertilization included as an explanatory factor. Soil physicochemical properties varied among systems, with diverse shade systems showing significantly lower bulk density, higher water-holding capacity, less acidic pH, and greater available phosphorus than unshaded coffee systems. Cumulative CO_2 respiration differed significantly among litter soil combinations ($p < 0.05$), indicating strong effects of litter type and soil origin on decomposition. Mixed-species litter under diverse shade systems exhibited the highest decomposition rates and positive home-field advantage, with additional decomposition at home ($ADH_x = 7.289\%$), demonstrating enhanced microbial adaptation to native litter inputs. In contrast, Albizia monoculture and unshaded coffee litter showed weaker and more variable HFA responses. Phosphorus fertilization enhanced decomposition trends, particularly under diverse shade and Albizia systems, although treatment differences among phosphorus levels were not consistently significant. The findings demonstrate that shade tree diversity strengthens litter decomposition efficiency and promotes stronger HFA by improving litter quality, soil nutrient status, and microbial specialization. Integrating Albizia gummifera within diverse multi-species shade systems is therefore more beneficial than maintaining Albizia monoculture shade systems for sustaining nutrient cycling in coffee agroforestry landscapes.

Keywords: Home-field advantage; Litter decomposition; Coffee agroforestry; Shade tree diversity; Phosphorus fertilization.

INTRODUCTION

Coffee is widely cultivated in agroforestry systems that range from simple shade arrangements to complex multi-strata structures resembling natural forests (Siahaan et al., 2019). These systems integrate coffee plants with diverse shade tree species, enhancing nutrient cycling, biodiversity, carbon sequestration, and microclimate regulation (Gomes et al., 2020). Compared to unshaded systems, agroforestry improves soil chemical and biological properties, largely through litter inputs and decomposition processes (de Souza et al., 2012). Litter decomposition is a key ecological process that regulates nutrient release, soil organic matter dynamics, and carbon fluxes, thereby supporting the sustainability of coffee production systems (Asigbaase et al., 2021).

Decomposition is controlled by interactions among litter quality, decomposer communities, and environmental conditions. Climate and litter quality are dominant drivers, explaining a substantial proportion of global variation in decomposition rates (Gartner et al., 2004; Wang et al., 2013), while local-scale processes are shaped by the interaction between substrate characteristics, soil biota, and microenvironment (García-Palacios et al., 2016). In agroforestry systems, litter from different plant species varies significantly in chemical composition and structural traits, influencing decomposer activity and efficiency (Cornwell et al., 2008). This variability underpins the concept of the home-field advantage (HFA), where decomposers more efficiently process litter originating from their native environment (Fanin et al., 2016; Benito-Carnero et al., 2021). However, HFA effects are inconsistent across ecosystems, ranging from negative to strongly positive responses depending on litter diversity, environmental conditions, and microbial community composition (Ayres et al., 2009). In addition, mixed species litter often produces non-additive effects, frequently enhancing decomposition rates due to increased chemical heterogeneity and complementary resource use by decomposers (Jewell et al., 2015; Getaneh et al., 2022).

In tropical agroecosystems, phosphorus (P) availability is a major constraint on both plant productivity and microbial processes. In Ethiopia, where most coffee production occurs without fertilizer inputs (Bote and Struik, 2011), P limitation is likely to influence both litter quality and decomposition dynamics. Phosphorus is essential for plant growth, flowering, fruit set, and stress tolerance (Lin et al., 2015; Júnior et al., 2021), and also plays a critical role in microbial metabolism and organic matter turnover. Studies in P-limited tropical systems suggest that phosphorus addition can enhance decomposition directly by stimulating microbial activity or indirectly by altering litter chemistry and dissolved organic matter (Zhang et al., 2020; Soong et al., 2018). However, empirical findings remain inconsistent, with some studies reporting increased decomposition and CO_2 emissions, while others show neutral effects (Kaspari et al., 2008; Cleveland et al., 2006; McGroddy et al., 2004; Barantal et al., 2012). These inconsistencies indicate unresolved interactions between nutrient availability, litter quality, and decomposer specialization.

Despite the importance of litter decomposition in regulating soil fertility and carbon dynamics in coffee agroforestry systems, there is limited empirical evidence on how shade tree diversity, decomposer specialization (home-field advantage), and phosphorus availability interact, particularly in Ethiopia. Most studies have examined these factors independently, with little integration under field conditions. The contribution of shade tree litter to nutrient cycling and carbon sequestration in southwest Ethiopian coffee systems remains poorly quantified, and the variability in reported HFA responses further complicates understanding. In addition, the effects of phosphorus fertilization on decomposition and CO_2 emissions are inconsistent and context dependent. These knowledge gaps hinder the development of effective, evidence-based nutrient management strategies for sustainable coffee production.

This study aims to investigate the home field advantage (HFA) of litter decomposition in coffee agroforestry systems and to determine how litter origin, shade tree diversity, and phosphorus fertilization influence decomposition rates and CO_2 emissions. Specifically, it evaluates differences in decomposition between home and away litter soil combinations, examines the effect of litter diversity and quality on decomposition efficiency, and quantifies the influence of phosphorus addition on microbial mediated litter breakdown. By integrating these factors, the study clarifies the relative contributions of litter identity and nutrient availability in regulating carbon release and nutrient cycling in coffee agroforestry soils.

MATERIALS AND METHODS

Study Area Description

The study was conducted in the Gomma District of Jimma Zone, southwestern Ethiopia (7.14°–7.87° N latitude, 36.64°–39.94° E longitude), a region recognized for its high coffee production. Within the district, Choche Village was selected due to its strong coffee production potential, and smallholder farms were chosen based on management practices, shade systems, and the presence of unshaded coffee farms as controls. Three coffee agroforestry systems were identified: (1) diverse shade tree farms, dominated by *Albizia gummifera*, *Cordia africana*, *Croton macrostachyus*, and *Acacia* spp.; (2) mono-species Albizia-shaded farms representing simplified shade systems; and (3) unshaded coffee farms serving as controls. Within diverse shade tree farms, *Albizia gummifera* and *Cordia africana* were the most abundant, while other species occurred at lower and variable densities.

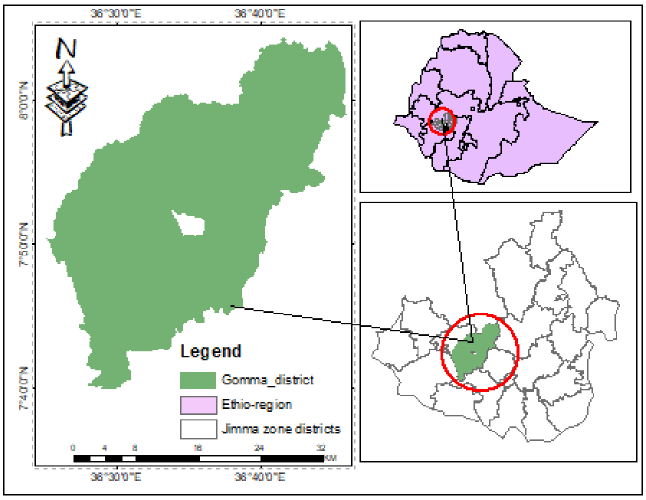

Figure -1: map of the study area

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Leaf litter sampling and preparation

Freshly senesced leaf litter was collected separately from each shade tree species between May 11–13, 2022. Samples were transported to the Soil Laboratory of JUCAVM and air-dried at room temperature for two weeks. Five independent leaf litter samples representing each species were stored for incubation experiments. For diverse shade tree farms, equal masses of dried litter from each species were ground and mixed prior to incubation. Mono-species (*Albizia gummifera*) and unshaded coffee litter were processed similarly.

Soil sampling and preparation

Soil samples were collected using a V-shaped technique for incubation, an auger for chemical analysis, and undisturbed core samplers for physical properties. For incubation experiments, soils were collected from beneath shade trees at 0–10 cm depth, where microbial abundance is highest (Hasenack, 2022). Soil from each sampling point was homogenized to represent the study area (Wallwork et al., 2022), with three farms per agroforestry system providing biological and physico-chemical replicates. Sampling points avoided edge effects and ensured canopy overlap.

For physico-chemical analyses, disturbed and undisturbed samples were collected from 0–30 cm depth (Bhowmik et al., 2019). Each site included ten sampling points, with six cores (6 cm diameter × 6 cm height) per point, totaling 60 cores per site and 180 cores overall. Subsamples were air-dried, sieved (2 mm mesh), and autoclaved at 121 °C for 30 minutes to facilitate controlled incubation. For microbial inoculation, 25% of each site's soil was sterilized, while the remaining 75% served as the inoculum source for microbial communities, microfauna, and mesofauna.

Soil laboratory analysis

Bulk density (BD) was determined by oven-drying cores at 105 °C and calculating the mass-to-volume ratio. Particle size distribution was determined using the Bouyoucos hydrometer method. Soil pH was measured in a 1:2.5 soil-to-water ratio with a digital pH meter. Organic carbon (OC) was analyzed using the Walkley–Black wet digestion method, and soil organic matter (SOM, %) was calculated by multiplying OC by 1.724. Available phosphorus (AvP) was determined using the Bray II extraction method with ammonium fluoride–HCl solution.

Biotic community extraction and soil inoculation

A two-month laboratory incubation was conducted to assess leaf litter decomposition under home-field and away-field conditions. Sterilized soils were re-inoculated with microbial, microfaunal, and mesofaunal communities extracted from 25% of unsterilized soil. Microbial inoculum was prepared by mixing soil with water, stirring, filtering, and applying the liquid fraction to sterilized soil, followed by a two-week pre-incubation in darkness.

Microfauna was extracted using the Baermann funnel method, and mesofauna were collected using Tullgren funnels with heat. Re-inoculated soils were maintained at 20 °C and 60% water holding capacity throughout incubation. A total of 48 specimen cups (160 mL) containing 50 g dry-weight soil were prepared across 12 treatments with four replications, including mixed litter, Albizia litter, coffee leaf litter, and soil-only controls. Litter additions consisted of 2 g of air-dried leaf litter per treatment. Home-field and away-field combinations were established among soil types, and phosphorus treatments (as TSP, equivalent to 75 kg ha^{-1}, 0.2 g per cup) were applied to selected home-field treatments. Successful inoculation was confirmed by fungal hyphae growth and mesofaunal activity prior to litter addition.

CO_2 gas sampling

Soil respiration was measured nine times over 60 days (days 1, 4, 12, 19, 26, 33, 40, 48, and 70) between 08:30 and 11:45 to approximate mean daily temperature. Initial measurements occurred on days 1 and 4, followed by weekly assessments. Soil moisture was monitored every two days and maintained throughout the experiment.

Incubation was conducted under dark conditions, with moisture stabilized for four weeks before litter addition and maintained for ten weeks after. Soil respiration was measured using a photoacoustic technique, with chambers inserted 2 cm above the soil surface, and rates expressed as µg CO_2 g^{-1} dry soil h^{-1}. Treatments included soils from diverse, Albizia, and unshaded sites, soil-only controls, and no-soil/no-litter controls for instrument calibration.

Equation 1. The following equation was used to calculate the gas fluxes (Faiz-ul Islam et al., 2020)

$$F = \frac{\Delta C}{\Delta t} * \frac{V}{A} * \frac{M}{Vs} * \frac{P}{Po} * \frac{273}{T}$$

Where ΔC is the change in gas concentration (ppm) over time interval Δt (h); V and A are the headspace volume (L) and reactor surface area (m^{-2}), respectively; M is the molecular mass of the gas; Vs is the molar volume at standard temperature and pressure; P and P_0 are the atmospheric and standard pressures; and T is the chamber temperature (K).

The trapezoid equation was used to calculate the cumulative emissions (Nigussie et al., 2017) 2

$$At_{(ab)} = \frac{(F_{ta} + F_{tb}) * (t_b - t_a)}{2}$$

Where $A_{t(a\beta)}$ is the cumulative emission between times t_a and t_b, and F_{ta} and F_t_b are the gas fluxes at those respective times.

The total cumulative emission was therefore calculated as: 3

$$\text{Total cummulative emission} = \sum At_{(ab)}$$

Global warming potential (CO_2-equivalents) was calculated as cumulative CO_2 × 1 (IPCC, 2013). Soil moisture was maintained at 60% water holding capacity, with moisture and minimum air temperature recorded during sampling.

Home-field advantage (HFA) calculation.

HFA indices were estimated for mixed tree leaf litter and *Albizia gummifera* litter using paired plots (Ayres et al., 2009). HFA measures the change in litter decomposition at □home□ relative to □away,□ based on cumulative CO_2 production as an indicator of decomposition. The calculation follows an approach adapted from sports home away comparisons (Clarke & Norman, 1995). Mixed litter was denoted as (x) with soil from diverse shade systems (A), while *Albizia* litter (y) corresponded to mono-shade soil (B); unshaded soil was represented as (C). Decomposition (D) was expressed as CO_2 respiration. HDD and ADD represent home and away decomposition differences, respectively. Total HFA (H) was calculated across all litter types (N), with ADH indicating additional decomposition at home.

Equation 4. Home-field advantage was calculated using the following equations (Ayres et al., 2009):

$$HDDx = (DxA - DyA) + (DxA - DzA)$$

$$ADDx = (DxB - DyB) + (DxC - DzC)$$
$$H = (HDDx + HDDy + HDDz / (N - 1)$$
$$ADHx = HDDx - ADDx - H$$

Effect of phosphorous fertilizer on HFA of litter decomposition

Home-field soils were used to test the effect of phosphorus (P) fertilization on litter decomposition. Specimen cups contained either mixed shade tree litter (site A, x) or *Albizia* litter (y), with and without TSP fertilizer (75 kg P ha^{-1} yr^{-1}, Jimma Research Center). Fertilizer amounts were scaled for laboratory soils based on specimen cup soil volume, surface area, and bulk density relative to field conditions, controlling for other variables.

HFA response to P addition was interpreted as: ADHxp > 0, slower decomposition than expected (negative effect); ADHxp = 0, no effect; ADHxp < 0, faster decomposition than without P (positive effect), indicating increased HFA.

Equation- 5. Equation for fertilizer effects

$$ADHxp = HDDx - HDDpx$$
$$HDDxp = (DxpA - DxA)$$

Data analysis

Additional decomposition at home (ADH) was calculated for mixed shade tree litter and *Albizia* litter across home- and away-field soils in each replicate. T-tests were used to assess significant differences ($P < 0.05$) between treatments, including home vs. away and with vs. without P fertilizer, using ADH values (ADHx = HDDx – ADDx – H) for HFA. Home-field effects on respiration were evaluated via t-tests comparing HFA at each sampling point to zero. Mixed linear models with multiple comparisons assessed the effects of litter type and P addition on decomposition. Analyses were conducted in R 4.2.2 and Excel.

Soil physical and chemical properties

Soil textures were similar across all coffee farms. Bulk density (0–30 cm) was significantly lower ($p < 0.05$) and water-holding capacity significantly higher ($p < 0.05$) under diverse shade systems than under unshaded coffee (Table 1). Soil pH ranged from 4.8 to 5.86, with a mean of 5.33 (Table 1), and was significantly less acidic ($p < 0.05$) under diverse shade tree systems than under unshaded systems. Elevated acidity in unshaded farms is likely due to base cation leaching, runoff, erosion, and intensive management under high rainfall and temperature (Abebe et al., 2013).

Organic matter (OM) was highest in diverse shade systems (4.4–5.0%, mean 4.7%), followed by monoculture Albizia-shaded farms (3.0–4.2%, mean 3.6%) and unshaded coffee (2.56–2.8%, mean 2.68%). Although differences were not statistically significant ($p > 0.05$), the trend aligns with higher litter inputs from mixed tree species enhancing SOM accumulation (EthioSIS, 2015).

Available phosphorus (AvP) was lowest in unshaded systems (0.64 ppm), followed by Albizia-shaded systems (2.05 ppm) and diverse shade systems (4.13 ppm). Despite variation, all soils were classified as very low (<15 ppm) in available P (EthioSIS, 2015). Low P availability is likely due to strong fixation by Al and Fe in acidic soils, compounded by continuous nutrient removal (Kiflu et al., 2017).

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Table 1. Soil physio-chemical properties

Soil Type	Depth (cm)	BD (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	WHC (%)	pH (m/L)	LOM (%)	AvP (ppm)
DSS	0–30	1.00 ± 0.17	24.17 ± 7.03	22.28 ± 5.00	49.11 ± 9.87	53.00 ± 4.18	5.86	4.70	4.13
SSS	0–30	1.15 ± 0.14	24.30 ± 5.03	21.68 ± 5.29	51.27 ± 9.87	51.18 ± 5.18	5.33	3.60	2.05
UCS	0–30	1.27 ± 0.14	25.11 ± 5.03	20.39 ± 5.29	52.00 ± 9.87	45.41 ± 5.18	4.82	2.68	0.64

specification 1: - DSS refers to soils sampled from coffee farms with diverse shade tree species; SSS represents soils from coffee farms shaded by a single species (*Albizia gummifera*); UCS denotes soils from unshaded coffee systems (control). BD = bulk density; WHC = water holding capacity.

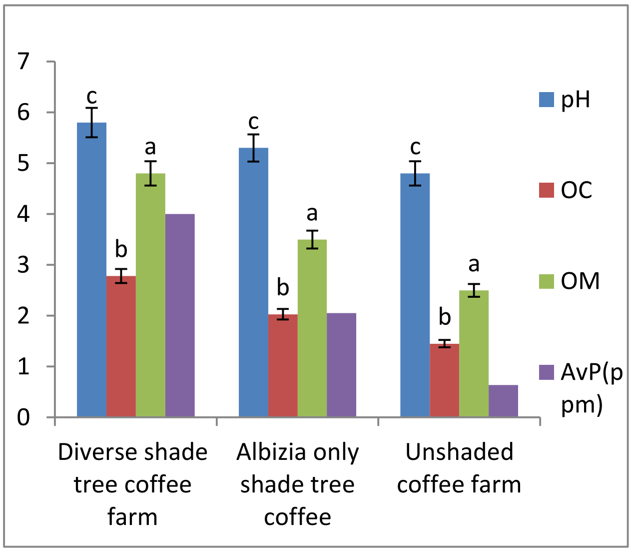

Figure 2. pH soil acidity, OC organic carbon OM organic matter and Available phosphorous

Laboratory soil incubation of leaf litter decomposition

General litter decomposition patterns

Cumulative CO_2 respiration during incubation varied significantly ($p < 0.05$) among litter–soil combinations (Figure 2; Table 2), highlighting the joint influence of litter quality and soil microbial communities. Mixed-species litter under home-field conditions exhibited significantly higher decomposition, indicating strong home-field advantage (HFA). This supports the hypothesis that soil biota specializes in decomposing familiar litter (Ayres et al., 2009a; Strickland et al., 2009) Mixed litter provides chemically heterogeneous substrates, including differences in nitrogen, lignin, and secondary metabolites, supporting diverse decomposer organisms and enhancing cumulative CO_2 emissions (Hobbie, 1996; Wardle et al., 2004; Gartner & Cardon, 2004). Away-field soils showed lower decomposition, reflecting less efficient microbial communities when exposed to unfamiliar litter (Strickland et al., 2009). Additional decomposition at home (ADH_x = 7.28%) further demonstrates complementarity effects among mixed litter components, likely through co-metabolism and nutrient transfer (Hättenschwiler et al., 2005). Laboratory incubation simplifies field conditions by excluding fauna, fluctuating moisture, and root interactions; however, it provides strong evidence that litter diversity and microbial adaptation are key determinants of decomposition.

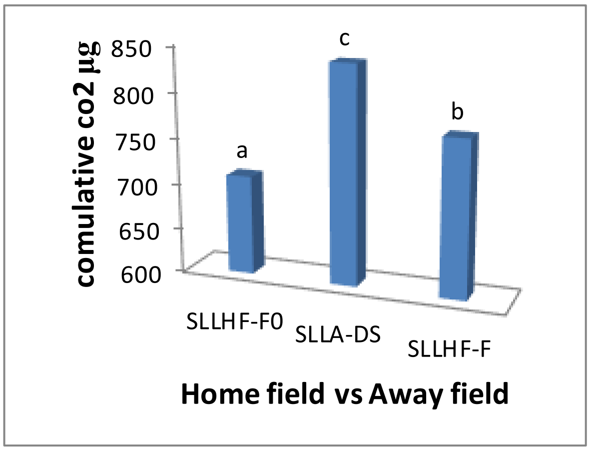

Figure 3. Diverse species of shade tree leaf litter mixtures and monoculture shade tree leaf litter were decomposed at home-field (with native soil) and away field (under others tree) and as a control coffee leaf litter at home-field and incubated with soil

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Table 2. Additional decomposition at home field of mixed diverse coffee shade tree leaf litters and total HFA.

Those used for home-field advantage of litter decomposition calculation	CO2 emission %
Home field decomposition deference of diverse shade tree species litter (HDDx)	729.705
Away field Decomposition Deference of diverse shade tree species litter (ADDx)	714.546
H total HFA for all litters combined	7.87
Additional decomposition at home for diverse shade tree species mixed litters ADHx	7.289

Home-field advantage in co$_2$ fluxes across shade categories

HFA varied significantly ($p < 0.05$) among shade categories and litter types (Figures 4 and 5). Mixed-species litter consistently exhibited higher cumulative CO$_2$ flux at home sites compared to away sites, while Albizia monoculture and unshaded litter showed smaller differences. Violin and box plots revealed wider variability and higher median CO$_2$ flux for mixed litter, indicating efficient microbial decomposition under native soils.

Variation in HFA is explained by microclimatic, chemical, and biological conditions. Mixed-species litter benefits from higher soil moisture, moderated temperature, and enhanced microbial enzyme activity (Gartner & Cardon, 2004). Soil chemical properties, such as higher pH under shaded systems, support microbial growth, while acidic unshaded soils suppress decomposition (Dawson et al., 2023; Getachew et al., 2023). N-fixing trees such as Albizia and Acacia improve soil fertility, reducing acidity and enhancing microbial-mediated litter breakdown. Phosphorus availability is higher under diverse shade, supporting microbial growth and functional complementarity (García-Palacios et al., 2016; Wang et al., 2013).

Litter quality also contributed: mixed litter exhibits chemical heterogeneity (lignin, cellulose, N), supporting diverse microbial communities, whereas Albizia litter is more uniform, limiting microbial specialization, and unshaded litter is nutrient-poor and recalcitrant (Gartner & Cardon, 2004; García-Palacios et al., 2016). Increased SOM under diverse shade improves soil structure, moisture retention, and aeration, enhancing microbial activity and reinforcing HFA (Jewell, 2013).

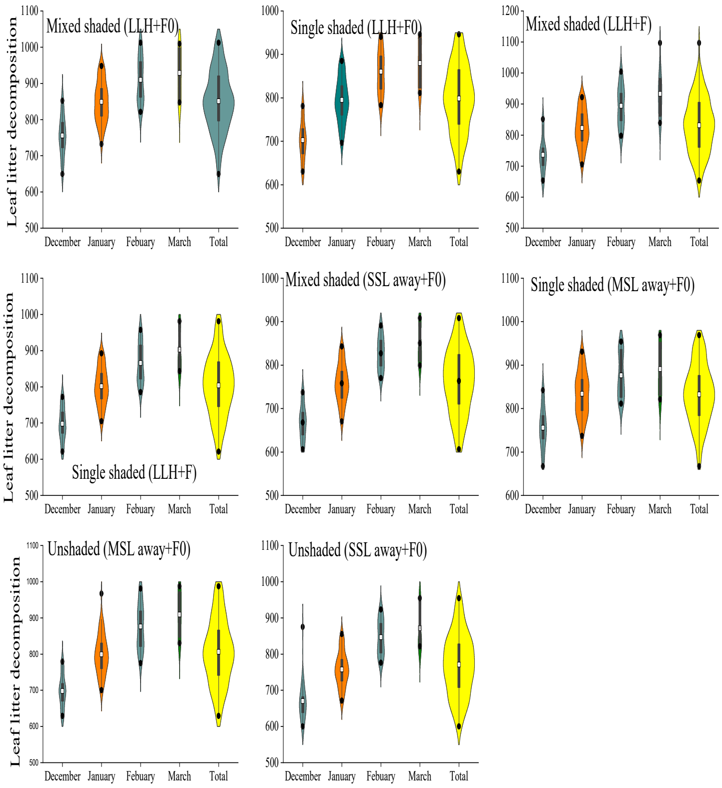

Figure 4. Violin and box plots showing the home field advantage (HMFA) of litter decomposition under different shade categories. *White box in the center represents mean values. Dark dots represent 95% confidence intervals (CIs). LLH represents leaf litters on home field soil, SSL represent single species leaf litter, and MSL represent mixed species leaf litters.*

Cumulative co$_2$ flux and decomposition differences

Cumulative HFA calculations (Figure 5) showed that HDDx (mixed-species litter) remained consistently positive, while HDDy (Albizia) and HDDz (unshaded) were lower and more variable. ADHx for mixed litter increased over time, confirming HFA presence. Early decomposition peaks in away soils were absent, indicating microbial acclimation is required for unfamiliar litter. Soil moisture ($r = 0.95$) and temperature ($r = 0.70$) strongly correlated with decomposition rates, emphasizing the influence of microclimate.

Higher soil pH and phosphorus under shaded systems enhance microbial growth, particularly for P-limited decomposers (Notaro et al., 2022; Xavier et al., 2011). Mixed-species litter supports a wider range of microbial functional groups, enabling sustained decomposition, whereas Albizia-only and unshaded litter support fewer niches (Gartner & Cardon, 2004; Hättenschwiler et al., 2005). Home microbial communities conditioned by local litter inputs were more efficient, and increased SOM further supported microbial activity and sustained CO$_2$ flux (Jewell, 2013).

The cumulative CO_2 flux results indicate that HFA is driven by litter diversity, soil microclimate, nutrient availability, and microbial adaptation. Stronger and more consistent HFA in mixed-species litter highlights the ecological importance of maintaining shade tree diversity to enhance decomposition and nutrient cycling (García-Palacios et al., 2016; Wang et al., 2013).

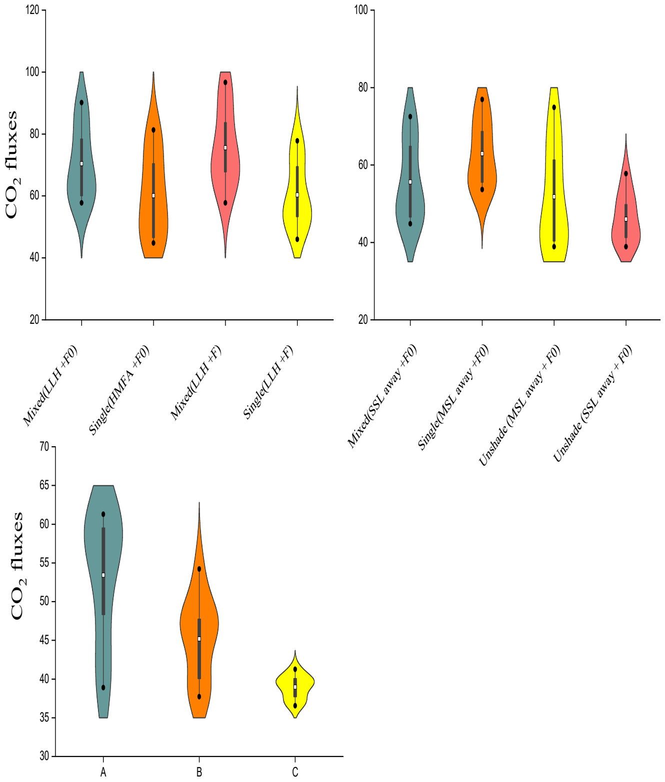

Figure 5. Violin and box plots showing the home field advantage (HMFA) CO2 fluxes under different shade categories.

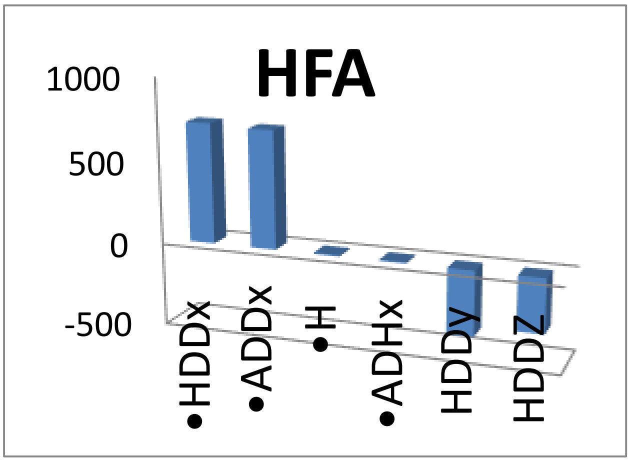

Figure 6. Using cumulative CO2 flux HFA calculation results.

CONCLUSION

The study demonstrates that litter decomposition in coffee agroforestry systems is strongly influenced by HFA, with mixed-species litter under diverse shade tree systems exhibiting the highest decomposition rates and cumulative CO_2 flux. Enhanced HFA results from interactions among litter chemical diversity, favorable microclimatic conditions, improved soil chemistry, and specialized microbial communities. Monoculture Albizia litter and unshaded litter exhibited weaker HFA, highlighting the limitations of simplified systems in supporting microbial functional diversity.

Based on these findings, it is recommended that coffee agroforestry systems maintain and promote diverse shade tree species to enhance litter diversity, stimulate microbial activity, and improve nutrient cycling. Phosphorus management should be integrated with shade tree diversity to optimize decomposition and maintain soil fertility. Regular monitoring and management of soil pH and soil organic matter are critical to sustaining microbial communities and maintaining efficient decomposition processes. Incorporating mixed-species litter inputs in agroforestry interventions can further maximize home-field advantage and support essential ecosystem services. Finally, long-term, field-based studies are needed to validate laboratory findings and to better understand the dynamics of HFA under natural environmental conditions.

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Conflict of Interest

No conflict of interest was reported by the Authors

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