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Nutrient dynamics and decomposition of agroforestry litter in acidic soils of Uasin Gishu County, Kenya

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Multiple forms of biomass, including litter, herbaceous, and woody biomass emanating from agroforestry systems, have numerous environmental and socioeconomic benefits, including improved soil health, biodiversity, carbon sequestration, and diversified income. These benefits are crucial to sustainable production. Despite agroforestry's significant contribution to sustainable food production, less attention is given to litter mass decomposition and its mechanisms of nutrient release and cycling. A study to assess the influence of agroforestry litter quality on decomposition and nutrient release in acidic soils of Uasin Gishu County, Kenya, was conducted at the University of Eldoret. The hypothesis was that the litter type of three agroforestry species - Gliricidia, Leucaena, and Sesbania - affects the rate of decomposition, nutrient release pattern, and the chemical characteristics of acidic soils. Results from the study revealed a significant (P≤0.05) influence of agroforestry litter type and initial litter quality on the rate of decomposition and nutrient dynamics in the order of Sesbania > Gliricidia > Leucaena. Sesbania showed superior litter quality, recording the highest OC (48.1%), N (25.9 g kg^{-1}), and Cu (0.35 ppm), and the lowest concentration of lignin (18.0%), cellulose (24.0%), and the lowest C:N, L:N, L:PP, L:P:N, and L:N:P ratios, hence the highest rate of decomposition (k=0.04). Nutrient release was in the order of Fe=Cu>K>Ca>Mg=Mn>N=Zn>P for Gliricidia, Ca>Cu>K=Mn>P>Zn>N for Leucaena, and Ca>Cu>Mn=Mg>P=K>N>Zn for Sesbania. Although there were no significant differences in nutrients released from the three litter types, Sesbania recorded the fastest release of N, P, Cu, and Mn, contributing about 3.2% SOC, 25.5 kg P ha^{-1}, and 11.4 kg K ha$_{-1}$ to the soil. Mean soil enrichment (ER=1.1, 1.5, and 2.5) for SOC, P, and K, respectively, indicates the potential of agroforestry litter mass of Sesbania sesban in nutrient cycling. These findings provide insights into the crucial role of agroforestry litter in the cycling of macro and micronutrients, hence enhancing soil ecosystems and sustainable production. However, further studies involving different litter types in multiple agroecological zones are needed to assess the impacts of other environmental factors on nutrient release mechanisms in acid soils.

Key words: Climate change mitigation, enrichment ratios, litter chemistry, nutrient cycling, soil ecology.

INTRODUCTION

Agroforestry is an important climate change mitigation and adaptation strategy, aligning with key components of

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the Sustainable Development Goals (SDGs), including the maintenance and restoration of soil quality (SDG#2) and carbon sequestration (SDG#13), hence sustainable food production (GSDR, 2023). Studies by Rizvi et al. (2019), Yadav et al. (2021), and Willmott et al. (2023) highlight the ecological benefits of agroforestry as a multifunctional land-use approach, including the provision of fodder, biofuel, soil conservation, and restoration of soil health through litter deposition across various agroecological zones. Globally, agroforestry systems enhance biodiversity, improve overall biomass production, contribute to soil and water conservation by reducing runoff and soil erosion, and minimize the detrimental effects of waterlogging and drought (Quandt, 2020). According to Dagar et al. (2020) and Gupta et al. (2020), agroforestry serves as the foundation for carbon sequestration, nutrient cycling, and supplying essential plant nutrients to the soil through various biochemical processes in soils. Multiple forms of biomass, including litter, herbaceous, and woody biomass emanating from agroforestry systems, have numerous environmental and socioeconomic benefits, including improved soil health, biodiversity, carbon sequestration, and diversified income, among others, which are cardinal to sustainable production (Gupta, 2020; Mukhlis et al., 2022). Plant litter mass is critical for the accumulation of soil organic matter (SOM), carbon organic carbon (SOC), and the recycling of essential nutrients in agroecosystems (Chao et al., 2019; Song et al., 2023) and is often cited as the key factor controlling the efficiency of the decomposition cycle and nutrient release globally (Wang et al., 2021; Su et al., 2021). Litter deposition is a key indicator of soil health, sustainable land use, and agricultural productivity. This is triggered by various interactions between litter mass, the environment, and soil organisms through biogeochemical processes resulting in decomposition and subsequent release of metabolites and nutrients to the environment (Zhang et al., 2023). Productivity and stability in soil ecosystems are mainly supported by litter decomposition (Elias et al., 2020). It is an ecological process through which plant litter is transformed into easily available minerals for utilization by plants and soil microbes (Verma et al., 2022). During decomposition, litter enters the soil ecosystem and is converted into nutrients due to biological, chemical, and physical processes, such as the mineralization of nitrogen and phosphorus, thereby contributing to nutrient cycling (Su et al., 2021). The chemical characteristics of litter mass constitute a complex mixture of substances, such as carbon, cellulose, lignin, polyphenols, macronutrients nitrogen (N) and phosphorus (P), and cations calcium (Ca), magnesium (Mg), and potassium (K), all of which influence the rate of decomposition and hence soil fertility (Pang et al., 2022; Song et al., 2023).

Leaf litter chemistry is a key determinant of litter decomposition (Giweta, 2020), nutrient cycling (Song et al., 2023), microbial activities (Bourget et al., 2023), SOM formation, and allelopathic effects within soil ecosystems (Scavo et al., 2019). The release of nutrients from decomposing litter affects nutrient cycling, soil health, and crop biomass yields; thus, understanding the principles governing litter decomposition is key to sustainable agricultural production. Several studies (Awazi and Tchamba, 2019; De Giusti et al., 2019; Amadu et al., 2020) in Sub-Saharan Africa (SSA) highlighted the positive effects of agroforestry on the physicochemical characteristics of agricultural soils, including enhanced SOC, nitrogen (N), phosphorus (P), and basic cations. Changes in soil chemical characteristics and maize yields under agroforestry systems have been documented in Kenya (Nyberg et al., 2020; Baier et al., 2023). Studies by Quandt (2020) and Sommer et al. (2025) suggested agroforestry as a sustainable option for enhancing SOC and phytoremediation of degraded soils. However, litter quality and quantity of different agroforestry species determine the efficiency of litter mass in enhancing the physico-chemical characteristics of soils in agroforestry systems. Panwar et al. (2022) attributed variation in biomass production and carbon sequestration in agroforestry systems to environmental factors and the species adopted. The role of agroforestry in enhancing soil fertility status has been emphasized as a climate-smart technology in Africa, especially under smallholder farming systems, largely characterized by low external input (Mbow et al., 2014; Sarkar et al., 2020). Biomass production under agroforestry systems is generally limited by climatic factors, species types, and agronomic practices (Veste et al., 2024). Climate variability (temperature and precipitation) in temperate and arid regions affects litter production, litter chemistry, rate of decomposition, and nutrient release (Sambou et al., 2024). In Kenya, agroforestry renders multiple benefits, including biofuel, fodder, shade, and soil conservation at the household level (Kitonga et al., 2020; Syano et al., 2023). Hedgerow, intercropping, strip-cropping, and woodlots are the main agroforestry practices in Kenya. Species such as Eucalyptus, Grevillea, and Leucaena are used mainly for timber and firewood, while the biomass of shrubs like Calliandra and Sesbania are utilized for fodder and soil fertility management (Muthuri et al., 2023).

Soil fertility decline in the country poses challenges to agricultural production and food security as more than 13% (7.5 million ha) of agricultural soils in the country. Such conditions contribute to Fe, Al, H and Mn toxicities in soil solution, and corresponding deficiencies of molybdenum (Mo), Ca, Mg, and K. Nyberg et al. (2020) cited increased concentrations of Al^{+3} ion below pH 5.5 as the main constraint to crop production, especially among smallholder farmers, the majority of whom cannot effectively mitigate the effects of soil acidity. There is limited information on the effects of litter decomposition on the dynamics of macro and micronutrients in soils as

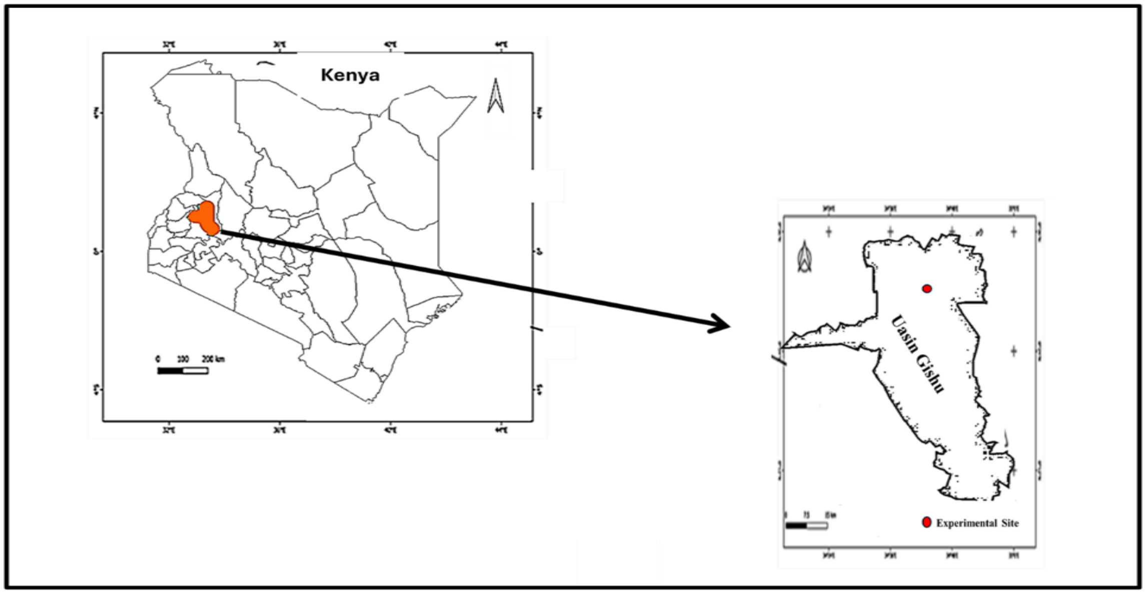

Figure 1. Map of Kenya depicting the study site.

previous decomposition studies in Kenya focused mainly on the contribution of litter to SOC, N, P, and K stocks (Mugendi, 1997; Walela et al., 2010). Additionally, agroforestry adoption in soil fertility management under smallholder agricultural systems in the country is low due to several socio-economic factors including land size, cultural practices, and the economic importance of the agroforestry species adopted (Nyberg et al., 2020; Pello et al., 2021). Therefore, this study aimed to assess the influence of agroforestry litter quality on decomposition and nutrient release in acidic soils.

METHODOLOGY

Study location

The study was conducted from October 2022 to January 2023 at the University of Eldoret, located in Kimumu Ward, Uasin Gishu County, at longitude 35° 18' 20'' E and latitude 0° 34' 36'' N (Figure 1). The study site is situated at an altitude of 2140 m above sea level along the Eldoret-Ziwa Road, off Iten Road, in Moiben Sub-County (GOK, 2020). Uasin Gishu is one of the food-producing regions in Kenya, attributed to its production of wheat, Irish potatoes, and tomatoes in the upper Rift Valley region. Ferralsols and Nitisols are the dominant soil types in Uasin Gishu County, with several limitations, including deficiencies of N, P, Ca, Mg, and micronutrients. The study area is categorized as a low highland agro-ecological zone (LH4) with Ferralsols (GOK, 2020).

Data collection

Soils

Soil samples were collected from the experimental area with the aid of a soil auger at a depth of 0-30 cm before the incubation of litter bags, at the time of litter mass sampling, and at the end of the experiment. A total of 70 soil samples were collected, air-dried, and sieved through a 2-mm sieve before being sent to the Department of Soil Science Laboratory for physicochemical analysis.

Biomass

Fresh biomass from three agroforestry trees (Gliricidia, Leucaena, and Sesbania) was collected from agroforestry plantations established at the University of Eldoret Farms. Litter mass (leaves and twigs) of the selected agroforestry species were collected from the most recently matured part of each plant following the protocols described by Bärlocher et al. (2020) and sent to the Department of Soil Science Lab at the University of Eldoret for chemical analyses. Before analysis, samples were air-dried in a greenhouse for three days and placed in an oven at 70°C for 48 h to maintain constant weight (Palm et al., 2001). Biomass samples were sieved through a 1-mm sieve, before chemical analysis.

Litter bag experiment

Litter decomposition and nutrient release patterns of agroforestry biomass (litter type) were assessed using the fine mesh litter bag technique (Knacker et al., 2003) under field conditions for 100 days (from 7th October, 2023 to 15th January, 2024). Twenty (20 g) of biomass (litter type) representing three agroforestry species were placed in litter bags of 20 × 30 cm with a mesh size of 2.0 mm and incubated in the soil at 10 cm depth. The experiment was laid out in a 3 × 5 × 3 randomized complete block design, with 3 L types (*Gliricidia sepium, Leucaena leucocephala* (Lam.) de Wit, and *Sesbania sesban*). Forty-five litter bags were deployed in the soil, while 15 litter bags were kept in the laboratory as control amounting to a total of 60 litter bags, sampled at 18, 36, 54, 72, and 100 days. At the designated sampling time, nine litter bags (representing 3 replicates of the three-litter type) were removed from the soil, double rinsed, with tap water and distilled water to remove soil particles and sediments. The remaining litter mass was air dried along with 3 L bags of the control samples were air-dried for three days in a greenhouse and placed in an oven at 70°C for 48 h to maintain constant weight, analyzed to determine changes in initial litter quality as prescribed by Okalebo et al. (2002).

The litterbag technique is a common method for studying the decomposition processes of litter mass in terrestrial ecosystems (Nakatsuka et al., 2020). This technique involves the enclosure of fresh litter in fine mesh bags, buried in the soil and collected at periodic intervals to measure the remaining mass. The size of the mesh is chosen to minimize excessive particle loss and allow access to all organisms during the various stages of decomposition.

Mean litter mass loss: This was assessed as litter mass remaining (%) after designated time t, and was calculated as follows:

$$\% \text{ Mass remaining} = (Wi / W0) \times 100 \quad (1)$$

where Wo = initial biomass weight; Wi = biomass weight at sampling time.

The relationships between the percentage of remaining litter mass and sampling time was assessed by the negative single exponential decay model by Olson (1963) using the following formula:

$$X_t = X_0 \times e^{-kt} \quad (2)$$

where X_t is the amount of litter at time t, X_0 is the initial amount, and k^t is the decomposition rate.

Nutrient release (%) was calculated as follows:

$$\%\text{Nutrient released} = [(C_0 \times M_0)\ (C_t \times M_t)] / (C_0 \times M_0) \times 100 \quad (3)$$

where C_0 = the initial nutrient concentration, and C_t = the nutrient concentration at time t.

The rate of litter decomposition (decomposition constant) was calculated using the initial-order reaction kinetics and exponential decay models formula following (Atkins, 2010):

$$K= - [\ln (X_f/X_i)]/t \quad (4)$$

where k = decomposition rate, X_f = biomass dry weight at the end of the experiment, X_i = biomass dry weight at the beginning of the experiment, and t = the number of days.

Half-life, a more practical measurement indicating the time lapsed until half of the mass of the plant material has been lost by decomposition (Olson, 1963) was calculated following (Bockheim et al., 1991):

$$T_{50} = \ln(0.5) / k^t \quad (5)$$

where $\mathbf{T_{50}}$ **=** litter half-life; ln = natural log, k^t = decomposition rate at the designated harvest time.

Enrichment ratio (ER), the ratio of nutrient concentration to the source of nutrients, often used as an index of soil productivity, was used to evaluate the effectiveness of litter in depositing nutrients released during decomposition. The enrichment ratio was calculated following (Tesfahunegn and Vlek, 2014):

$$ER = N_f/N_i \quad (6)$$

where ER = enrichment ratio; N_f = nutrient concentration in soils at the end of litter incubation, known as treated plot, and N_i = initial nutrient concentration of soils before incubation of litter mass, or control plots. An ER = <1: indicates a negative response to treatment; ER= 1.0: indicates no change, ER= >1.0: indicates a significant response to treatment.

Soil analysis

Soil bulk density (BD) was determined using the core method (Robinson, 1994), particle size distribution was determined by the Bouyoucos Hydrometer method, pH was determined in 1: 2.5 H_2O, soil organic Carbon (SOC) was determined by the Potassium Dichromate method (Nelson and Sommer, 1996), total nitrogen was determined by acid digestion (Bremner, 1996), available P was determined by the Olsen method (Olsen, 1965), and exchangeable cations (Ca, K, and Mg) were determined by the ammonium acetate method, and micronutrients (Cu, Fe, Mn, and Zn) were determined by the Ethylenediaminetetraacetic acid (EDTA) method (Norvell, 1984).

Biomass analysis

Nutrient concentrations of litter biomass were determined through various laboratory protocols prescribed by Okalebo et al. (2002). Total Nitrogen was determined using the Kjeldahl method, total P was measured through colorimetry using molybdenum blue (ammonium molybdate and Tin chloride) and a UV spectrophotometer at a wavelength of 660 nm. Potassium was determined using a flame photometer, while Ca, Mg, K, copper (Cu), zinc (Zn), manganese (Mn) and iron (Fe) were determined by Atomic Absorption spectrophotometer method in the Department of Soil Science laboratory at the University of Eldoret. Biomolecular analyses of organic carbon (OC), cellulose (CL), lignin (L), and polyphenols (PP) of litter types were conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) in Nairobi, whereas nutrient analysis was conducted following the acid detergent fibre (ADF) method prescribed by Okalebo et al. (2002).

Statistical analysis

Linear regression was used to describe the relationship between the rate of litter mass loss and time. One-way and two-way (ANOVA) were used to compare the rate of litter decomposition and the effect of litter type and time on litter mass loss and rate of decomposition, and the means were considered significant based on Tukey's Honest Significant Difference (HSD) test. A pair-wise comparison was used to determine the differences in initial soil characteristics and biomass quality. Characterization of litter quality was done as prescribed by Palm et al. (2001), while changes in initial soil characteristics were determined by soil enrichment ratio (Tesfahunegn and Vlek, 2014). All data were organized and analyzed in Microsoft Excel (2013) and R software, version 4.2.2 (R Core Team, 2023).

RESULTS

Soil characteristics

Chemical analysis showed that soil at the University of Eldoret farm is acidic and classified as rhodic Ferralsols that are strongly acidic (4.9), low in SOC (1.1%), total nitrogen (0.1%), available P (5.7 mg kg^{-1}), low to medium exchangeable K (1.2 cmol kg^{-1}), Ca (1.5 cmol kg^{-1}), and Mg (1.35 cmol kg^{-1}). Soil micronutrients: Fe (1.0), Mn (27.2 ppm), and Zn (5.3 ppm) were rated low, while the concentration of Cu (2.5 cmol kg^{-1}) was considered adequate, especially for maize production according to (NAAIAP and KARI, 2014) (Table 1).

Initial litter chemistry

The initial contents of lignin (27.2%), K (1.2 g kg^{-1}), and

Table 1. Physicochemical characteristics of soils in experimental plots before litter decomposition at UoE farms.

Variable	Unit	Value
Bulk density	(g cm^{-3})	1.3
SOC	(%)	1.1
pH	-	5.0
Total N	(%)	0.1
Available P	(mg kg^{-1})	1.1
Exchangeable K	(cmol kg^{-1})	0.2
Exchangeable Ca	(cmol kg^{-1})	1.5
Exchangeable Mg	(cmol kg^{-1})	1.3
Available Cu	(ppm)	0.8
Available Fe	(ppm)	6.8
Available Mn	(ppm)	28.7
Available Zn	(ppm)	3.8

Table 2. Initial litter quality of three agroforestry tree species used in the experiment.

Litter quality	Unit	Gliricidia	Leucaena	Sesbania	F value	Pr(>F)
Organic carbon	%	47.0	48.0	48.1	0.3	0.73
Cellulose	%	29.1	28.8	24.0	0.7	0.52
Lignin	%	27.2*	24.0	18.0	2.8	0.14
Polyphenols	%	5.5	9.0*	4.5	3.7	0.09
Nitrogen	g kg^{-1}	2.2	2.4	2.6	0.8	0.51
Phosphorus	g kg^{-1}	0.3	0.2	0.3	0.5	0.62
Potassium	g kg^{-1}	1.2*	0.1	0.1	4.3	0.07
Calcium	g kg^{-1}	0.6	0.1	0.1	1.5	0.30
Magnesium	g kg^{-1}	0.8*	0.7	0.1	2.8	0.14
Copper	mg kg^{-1}	0.2	0.3	0.4	0.7	0.55
Iron	mg kg^{-1}	1.3	1.4	1.4	0.1	0.93
Manganese	mg kg^{-1}	3.0	3.4*	3.3	2.4	0.14
Zinc	mg kg^{-1}	5.8	5.6	5.1	0.3	0.75

Means in the same column followed by ***,**, and * indicate significant difference at P(≤ 0.00), P(≤ 0.05), and P(≤ 0.1) respectively.

Mg(0.8 g kg^{-1}) in Gliricidia, and polyphenols (9.0%), and Mn (3.4 mg kg^{-1}) contents in Leucaena were highest and differed significantly at (P≤ 0.1). The lowest concentrations of lignin (18.0%), cellulose (24.0%), and Mg (0.1 g^{-1}) were recorded in Sesbania, whereas Leucaena biomass recorded the lowest concentration of P (0.2 g kg^{-1}) compared to the other litter types (Table 2).

Litter stochiometric ratios

Significant (P≤0.05) difference in litter stoichiometry ratios was observed with the highest C:P (199:1) N: P(10:1), and L:P (120:1), PP: N (0.4:1), and PP:P (4:1) recorded in Leucaena; while the highest L: N (12:1), CL: N (14:1) was recorded in Gliricidia. Whereas the highest CL:P (92:1) and lowest L: N (7.0:1) L:P (1:15), and PP: N were recorded in Sesbania. Carbon-to-Nitrogen (C:N) ratio ranged from 1:19- 1:22, but not statistically different among the litter types. The highest C: N ratio was recorded in Gliricidia, while the lowest was recorded in sesbania (Table 3). All the litter types recorded high quality C:N ratio (< 25:1), and low L:PP ratio (>25:1). However, the litter of sesbania showed superior quality, with C:P (85:1), L:N (7:1), L+P:N (20:1), and L:P:N (23:1) ratios in the medium category, compared to Gliricidia and Leucaena which recorded low ratings according to (Palm et al. (2001) (Table 4).

Litter mass loss and rate of decomposition

The trend of litter mass loss and rate of decomposition differed statistically P (≤0.05) with time but did not differ among litter types. Litter mass loss and decomposition constant were fastest at the beginning of the experiment

Table 3. Stoichiometric profile of litter types from three agroforestry litter types.

Stoichiometry	Gliricidia	Leucaena	Sesbania
C:N	22.0 (±1.7)[a]	20.0 (±1.7)[a]	19.0 (±1.7)[a]
C:P	21.0 (±7.8)[b]	199.0 (±7.8)[a]	185.0 (±7.8)[ab]
N:P	1.0 (±0.61)[b]	10.0 (±0.61)[a]	9.9 (±0.61)[b]
L:N	12.4 (±3.3)[a]	10.0 (±3.3)[a]	7.0 (±3.3)[b]
L:P	91.0 (±20.0)[ab]	120.0 (±20.0)[a]	60.0 (±20.0)[b]
CL:N	14.0 (±11.1)[a]	12.0 (±11.1)[a]	9.3 (±11.1)[ab]
CL:P	13.0 (±1.38)[b]	12.0 (±1.38)[b]	92.3 (±1.38)[a]
PP:N	0.3 (±0.01)[a]	0.4 (±0.01)[a]	0.2 (±0.01)[b]
PP:L	0.0 (±0.00)[a]	0.0 (±0.00)[a]	0.0 (±0.00)[a]
PP:C	0.0 (±0.00)[a]	0.0 (±0.00)[a]	0.0 (±0.00)[a]
PP:P	0.2 (±0.61)[b]	3.7 (±0.61)[a]	1.7 (±0.61)[ab]
L+PP:N	30.0 (±2.43)[a]	28.0 (±2.43)[ab]	20.0 (±2.43)[b]

Means in the same row followed by different letters indicate significant difference at P(≤ 0.05). C:N = carbon -to-nitrogen ratio; C:P = carbon -to- phosphorus ratio; N:P = nitrogen -to-phosphorus ratio; L:N = lignin-to-nitrogen ratio; L:P = lignin-to- phosphorus ratio; CL:N = cellulose-to- phosphorus; CL:N = cellulose -to-nitrogen ratio.

Table 4. Categorization of litter quality based on stochiometric ratios.

Litter type	C:N	C:P	L:N	L:PP	L+P:N	L:N:P
Gliricidia	22:1 H	21:1 H	12:1 L	91:1 L	30:1 L	41:1 L
Leucaena	20:1 H	199:1 M	10:1 M	120:1 L	28:1 L	50:1 L
Sesbania	19:1 H	185:1 M	7:1 M	60:1 L	20:1 M	23:1 M

H = high quality; M = medium quality; L = low quality.

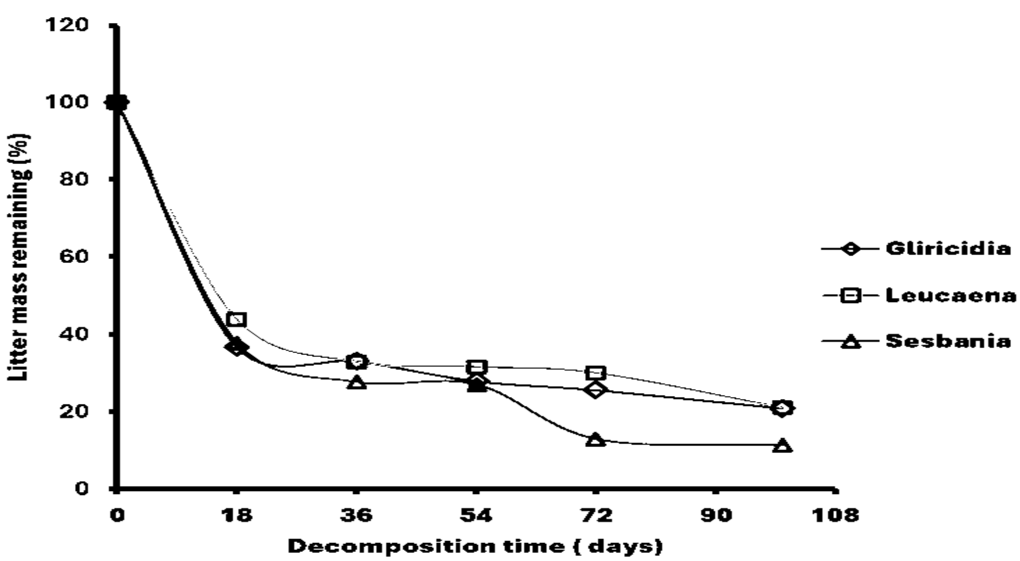

Figure 2. Litter mass loss of litter type from three agroforestry species for 100 days.

and steadily declined with time. The highest rate of mass loss (0.4 g day^{-1}) and decomposition (k=0.04) were recorded on day 18. Sesbania recorded the fastest rate of mass loss (89.0%), and the lowest decomposition constant value (k=0.01) at the end of experiment (Figure 2). The litter decomposition rate did not differ significantly among litter types, but the lowest decomposition rate and decomposition constant (k= 0.02 g day^{-1}) was recorded in Leucaena. Subsequently, a significant (P ≤ 0.05) difference in litter half-life was observed in the order of

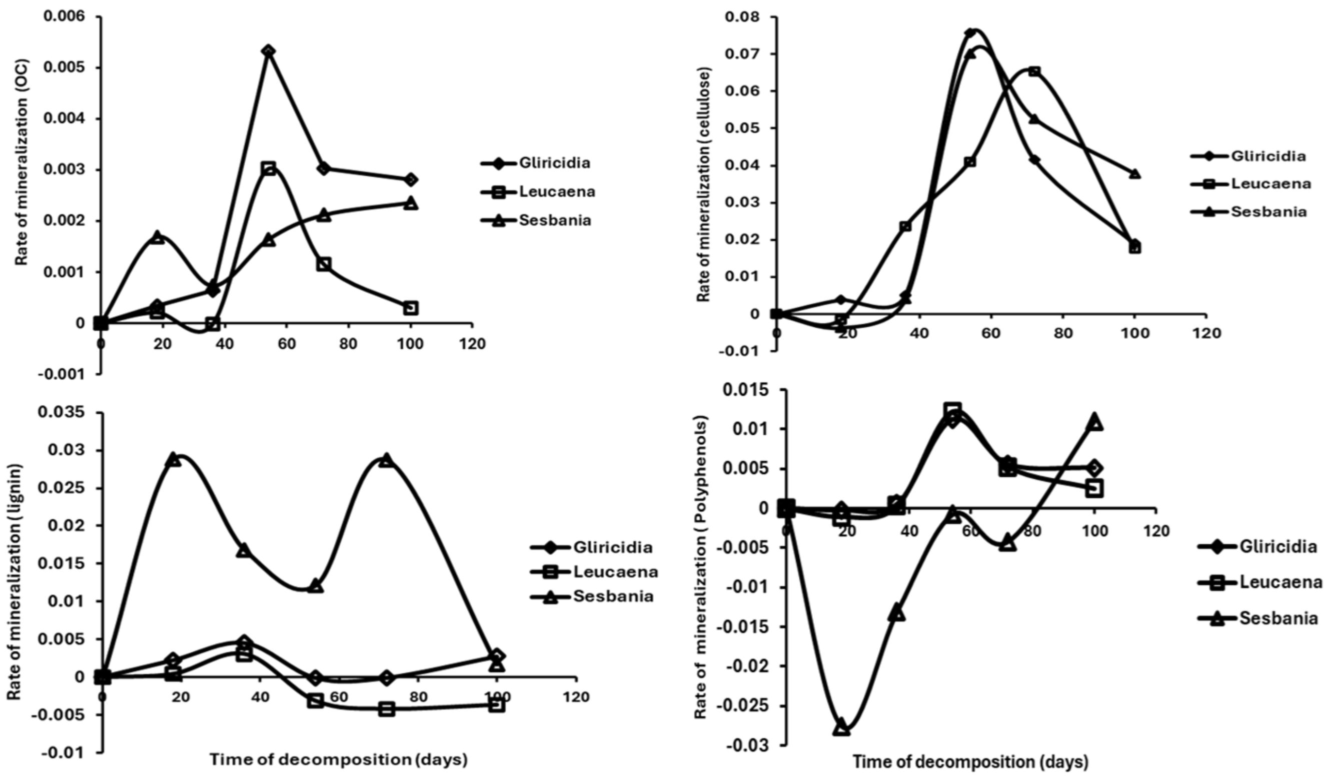

Figure 3. Mineralization of OC, cellulose, lignin, and polyphenols as influenced by time and litter type.

Leucaena> Gliricidia > Sesbania (t_{50} = 29 days), (t_{50} = 25days) and (t_{50} = 20 days), respectively.

Effect of litter chemistry on rate of mineralization and nutrient release

A significant P(≤0.05) relationship between time and the mineralization of OC, cellulose, lignin, and polyphenols was observed in all litter types. The rate of mineralization for lignin differed significantly P(≤0.05) among the litter types (P≤0.05), with the highest rate of mineralization (k= 0.03) recorded in Sesbania at days 18 and 72. However, the rates of mineralization for polyphenols, cellulose, and OC did not differ among the litter types, but increased rates of their mineralization were observed at day 54 for all litter types. Immobilization of OC, cellulose, and lignin was observed in Leucaena at days 36,18, and 54, respectively, while Sesbania recorded net immobilization of polyphenols between days 18 and 72 (Figure 3).

Similar trends were observed with nutrients released from litter mass. The was no significant difference in the amount of nutrients released, except for Fe, which differed significantly (P≤ 0.1) among the litter types. The highest release of Fe (99%) was observed in Gliricidia and the lowest (37%) was recorded in Sesbania at the end of the experiment. It was further observed that the rates of mineralization and nutrients released from biomass in the study were significantly (P≤ 0.05) influenced by time regardless of the litter type. Nitrogen, P, Mg, Cu, and Mn releases were the highest in Sesbania; K, and Fe in Leucaena, and Ca in Gliricidia. K, Ca, and Mn were slowest in Sesbania, while P, K, Cu, Fe, and Zn were slowest in Gliricidia (Table 5, Figure 4).

Effects of decomposition and nutrient release on soil chemical characteristics

The decomposition of agroforestry litter mass significantly increased SOC, available P, K, Mg, Cu, and Zn compared to the initial soil level (Figure 5). The results showed variation among litter types, with Sesbania and Leucaena having increased levels of P, Ca, Mg, and Zn above the initial soil level and those of Gliricidia. In contrast, no significant influence of litter type was observed in litter types, initial soil pH, and N. However, Fe and Mn decreased with litter decomposition in the study. The paired T-test showed a significant (P≤ 0.05) difference between the initial chemical characteristics of soil and post-litter incubation. Noticeably, mean SOC, pH, P, K, Mg, Cu, and Zn significantly increased by 36.4, 4, 146.0, 50.0, 15.4, 75.0, and 34.2% above initial soil characteristics at the end of the experiment (Table 5).

Table 5. Effect of litter type on decomposition rate (k) and time to 50% decomposition.

Litter type (n=45)	K-constant	Half-life	r^2	Rating
Gliricidia[a]	0.03	24.0	0.73	Medium
Leucaena	0.02	29.0*	0.77	Medium
Sesbania	0.04	20.0	0.87	Slow

[a]Mean of three replications; Mean in the same column followed by an asterisk (*) indicate a significant difference according to Tukey's HSD multiple comparison test.

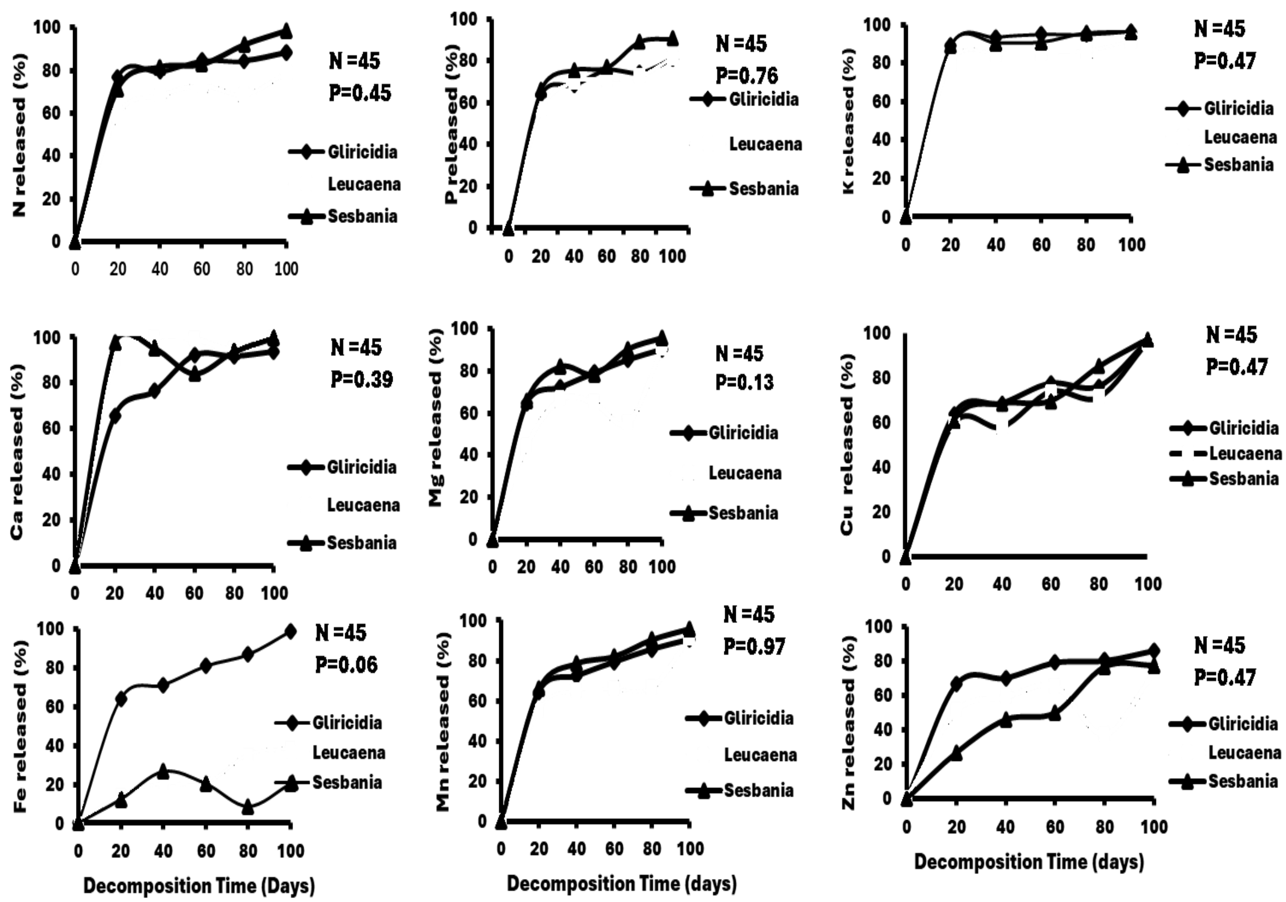

Figure 4. Effects of agroforestry litter type on the rate of nutrients released for 100 days of decomposition.

However, no change in N and Ca was observed, whereas, a decrease in Fe (-16.2%) and Mn (-6.6%) were recorded at the end of the experiment (Table 6).

Effects of litter type on soil fertility status

Assessment of soil fertility status using the nutrient enrichment ratio implied that litter type and decomposition significantly enhanced soil chemical characteristics. The mean effect of litter decomposition on soil characteristics is evidenced by increased ER values for SOC (ER = 3.0), P (ER = 3.0), K (ER =2.0), Mg (ER =1.2) Cu (ER =2.0), and Zn (ER =1.4) It was observed that Sesbania and Leucaena influenced ER values (ER= > 1.0) of P and Zn, compared to Gliricidia, however, no change in soil pH, N, and Ca were observed in this study (Table 6). The findings also showed that litter decomposition had positive effects on SOC and nutrient stocks as revealed by increased ER values ranging from 1.0 - 3.0 (Table 6). Sesbania and Leucaena showed superior abilities to enhance soil available P, Ca, Mn, and Zn, compared to Gliricidia which recorded ER values of 0.9, for Ca, Fe, Mn, and Zn. However, lower ER values (ER = 0.8-0.9)

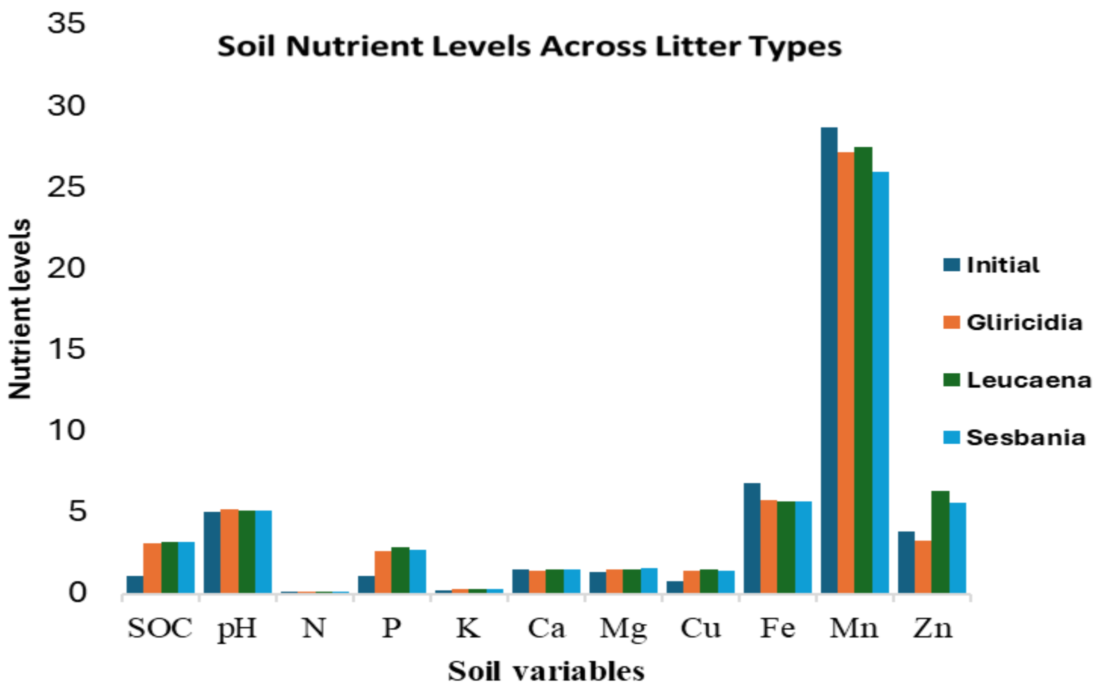

Figure 5. Influence of litter type on soil nutrient level at UoE farms.

Table 6. Changes in initial soil characteristics as affected by litter decomposition.

Soil characteristics	Initial	Final	Difference (Initial- final)	% Change
BD (g cm^{-3})	1.3*	1.2	-0.1	-7.7
SOC (%)	1.1	1.5*	0.4	36.4
pH (1:2.5 H_2O)	4.9	5.1**	0.2	4.1
N (%)	0.1	0.1	0	0.0
P (mg kg^{-1})	1.1	2.7***	1.6	145.5
K (cmol kg^{-1})	0.2	0.3***	0.1	50.0
Ca (cmol kg^{-1})	1.5	1.5	0	0.0
Mg (cmol kg^{-1})	1.3	1.5	0.2	15.4
Cu (ppm)	0.8	1.4***	0.6	75.0
Fe (ppm)	6.8***	5.7	-1.1	-16.2
Mn (ppm)	28.7**	26.8	-1.9	-6.6
Zn (ppm)	3.8	5.1*	1.3	34.2

Means in the same column followed by ***,**, and * indicate significant difference at P(≤ 0.00), P(≤ 0.05), and P(≤ 0.1) respectively.

were attributed to all litter types in this study (Table 7).

DISCUSSION

Impacts of soil chemical characteristics on litter decomposition

Soil characteristics revealed that soils at the experiment site are characterized as acidic (5.0) with low levels of SOC (< 2.0%), and deficiencies of macro (N= < 0.2%, P = < 30 mg kg^{-1}, and Ca = < 2.0 cmol kg^{-1}) and micronutrients (Fe = < 10 ppm, Mn = < 30 ppm, and Zn = < 5 ppm), which have negative consequences on the production of important food crops in Kenya, such as maize and beans, according to (NAAIAP and KARI, 2014). These conditions affect not only the availability of plant nutrients but also limit important microbial activities, including the decomposition of organic matter, and, hence, nutrient cycling (Wang et al., 2022; Naz et al.,

Table 7. Soil response to nutrients released from the decomposition of agroforestry litter mass.

Variable	Unit	Initial (T_i)	Gliricidia	Leucaena	Sesbania	Enrichment ratio* T_f/T_i)		
						Gliricidia	Leucaena	Sesbania
SOC	%	1.1	3.1	3.2	3.2	3.0	3.0	3.0
pH	-	5.0	5.2	5.1	5.1	1.0	1.0	1.0
N	%	0.1	0.1	0.1	0.1	1.0	1.0	1.0
P	Mg kg^{-1}	1.1	2.6	2.9	2.7	2.4	3.0*	3.0*
K	(cmol kg^{-1})	0.2	0.3	0.3	0.3	1.5	1.5	1.5
Ca	(cmol kg^{-1})	1.5	1.4	1.5	1.5	0.9	1.0	1.0
Mg	(cmol kg^{-1})	1.3	1.5	1.5	1.6	1.2	1.2	1.2
Cu	ppm	0.8	1.4	1.5	1.4	1.8	1.9*	1.8
Fe	ppm	6.8	5.8	5.7	5.7	0.9	0.8	0.8
Mn	ppm	28.7	27.2	27.5	26.0	0.9	1.0*	0.9
Zn	ppm	3.8	3.3	6.3	5.6	0.9	1.7*	1.5

*Enrichment Ratio (ER) <1.0 = negative effect of litter decomposition on soil characteristics; ER 1.0 = no change in soil characteristics; ER> 1.0 = positive influence of litter decomposition on soil characteristics.

2022). Henceforth, sustainable land use practices such as agroforestry and intercropping to improve soil structure, and moisture retention, and promote soil carbon sequestration, biodiversity, and nutrient cycling are important for sustainable production.

Litter quality

Findings of the current study revealed that the litter types under investigation were of medium to low quality, hence moderate to low rates of decomposition, according to (Palm et al. (2001). Litter mass of sesbania showed superior quality over the other litter types with low C: N ratio and moderate C:P, L:P, L:P:N, and L+P:N ratios, as evidenced by a faster rate of decomposition. Similar observations were made by Belele et al. (2022) who reported superior quality and faster decomposition rate of Sesbania over litter mass of *Cajanus Cajan* and *Flemingia macrophyll* in acidic soils of Burkiti kebele of the Dello-Menna district, a sub-humid in Ethiopia. Fast decomposition of Sesbania sesban with high N and medium L:PP contents as observed in this study concords with the reports of Mafongoya et al. (2008) who attributed faster decomposition to high nitrogen levels, low L:PP contents in the litter of Sesbania and Gliricidia.

Effects of litter quality and litter type on decomposition

The findings of the current study revealed that litter type significantly influenced decomposition, with Sesbania showing a higher rate of decomposition compared to Leucaena and Gliricidia. A higher decomposition constant value (k=0.04) observed in sesbania during the experiment can be attributed to lower initial concentrations of cellulose (24.0 g kg^{-1}) lignin (18.0%), and polyphenols (0.5%), C: N ratio (19:1), and high N (2.6%) compared to the other litter types. The findings of this study are in line with the findings of Gill et al. (2021) and Hou et al. (2021) who reported that lower concentrations of lignin and polyphenol facilitate fast decomposition of litter. The results further showed that litter type (Sesbania) with C: N < 20:1 decomposed faster than those with a higher C: N ratio, confirming the findings of Negash and Starr (2021) who reported that the relative availability of C and N to microbial communities determines the carbon and nutrient dynamics. Slower decomposition rates in Leucaena and Gliricidia could be attributed to higher cellulose and lignin contents, which resulted in slower decomposition rates. Similar observations were made by Gießelmann et al. (2011) and Negash and Starr (2021) in tropical acidic soil. However, these findings contradict the assumption that lowers C: N and lignin content are key indicators of litter decomposition. Studies by Akoto et al. (2022) and Ransedokken et al. (2024) emphasized the importance of secondary metabolites, such as phenolic compounds, in litter decomposition, and their ability to inhibit microbial activity, even in the litter with low C: N ratios or low lignin contents. A study Xiang et al. (2024) found that the rate of litter decomposition increased in nutrient-rich environments in litter, but was constrained in nitrogen-limited environments, resulting in a slower decomposition of litter with low C: N ratios due to microbial nitrogen constraints (Liu et al., 2024). However, the trend of litter mass loss and rate of decomposition observed in the study were rated low to moderate according to Bärlocher et al. (2020). Nutrient dynamics of the litter types in this study suggest that in addition to litter quality, initial soil characteristics contribute to the rate of decomposition and nutrient release. Low SOC and the deficiency of macronutrients N, P, Ca, and Mg contributed to the rate of nutrient release thus, the chemical characteristics of soils at the end of the experiment. The average rate of litter mass decomposition (k=0.03 day^{-1}) in this study is typical of humid tropical regions of the world, where temperature and rainfall are appropriate to stimulate microbial interactions, hence fast litter decomposition and nutrient release. These findings agree with the findings of Su et al. (2023) and Wang et al. (2024) who observed fast decomposition of agroforestry litter mass under humid conditions compared to lower rates of decomposition (k= < 0.01) in arid and semi-arid regions.

Enrichment ratio values ER > 1.0, correlated with increased SOC, P, and K amounting to 3.2% SOC, 25.5 kg P ha^{-1}, and 11.4 kg K ha^{-1} released into the soil, highlighting the significance of litter chemistry in enhancing and management of soil fertility. Non-response of soil pH (ER=1.0) and N (ER=1.0) as observed in the study implies the roles of initial soil characteristics and litter quality on decomposition in acidic soil (Pichon et al., 2020). The negative changes in soil-available Ca, Fe, and Mn, contents at the end of the experiment are indicative of the net immobilization of these elements and the inherently low SOC and pH as well as deficiencies of essential plant nutrients, which have the potential to affect microbial immobilization and nutrient cycling (Pichon et al., 2020; Wang et al., 2022). The nutrient release pattern in the current study was in the order of Gliricidia: Fe=Cu>K>Ca>Mn>N=Zn>P; for Leucaena: Ca>Cu>K=Mn>P>Zn>N; and Sesbania: Ca>Cu>Mn=Mg>P=K>N>Zn. The dynamics of secondary macronutrients from decomposing litter in this study showed that the highest release of K (97%), Ca (99%), and Mg (99%) were observed in Gliricidia, Leucaena, and Sesbania, respectively. The fast release of K as observed in this study conforms with the findings of Bessaad and Korboulewsky (2020) who reported a significant release of K due to the high mobility of this nutrient through leaching from litter decomposition, because K does not constitute organic structures in plant tissues, hence it is easily removed even in the early stages of the process. Contrary to the findings of the study by Yang et al. (2022) and Tie et al. (2023) that reported a slower release of Ca and Mg from agroforestry litter types in tropical regions, this is evidence that their rates of release are dependent mainly on decomposition through biotic activity instead of direct leaching.

Conclusion

The objective of the study was to assess the influence of agroforestry litter quality on the decomposition and nutrient release in acidic soils of Uasin Gishu County, a humid agroecological zone of Kenya. The results showed that soils at the University of Eldoret are acidic and low SOC, in macro and micronutrients, and medium to adequate in Cu, and K, respectively. Decomposition constant values (k = 0.02 - 0.04 g day^{-1}) showed a significant influence of Sesbania on the rate of litter mass loss over time, also releases of Nitrogen, P, Mg, Cu, and Mn releases were highest in Sesbania; K, and Fe in Leucaena, and Ca in Gliricidia. Potassium, Ca and Mn were slowest in Sesbania, while P, K, Cu, Fe, and Zn were slowest in Gliricidia. It was also revealed that litter type initial litter quality and stoichiometric ratios such as C: N, N:P, L: P, PP:P, CL: N, and CL:P significantly influenced litter decomposition. However, the net immobilization of OC, cellulose, lignin, polyphenols, and the longest time (29 days) to attain decomposition half-life were observed in Leucaena. The enrichment ratio showed that litter decomposition significantly influenced SOC (ER = 3.0) available P (ER= 3.0) and K (ER=1.5), hence the potential of Sesbania to recycle 3.2% SOC, 25.5 kg P ha^{-1}, and 11.4 kg K ha^{-1} within the soils. These findings give insight into the crucial role of agroforestry litter in soil carbon sequestration, the cycling of macro and micronutrients and the enhancement of soil ecosystems, hence sustainable production. However, further studies involving different litter types in multiple locations within Uasin Gishu County are needed to assess the impacts of other environmental factors on nutrient release mechanisms in acid soils.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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