PREDICTING THE DECOMPOSITION RATE, MASS LOSS, AND NUTRIENT RELEASE OF SINGLE AND MIXED LEAF LITTER TYPES USING DECOMPOSITION MODELS IN THE NORTHERN GUINEA SAVANNAH OF NIGERIA †

[MODELOS DE DESCOMPOSICIÓN PARA LA PREDICCIÓN DE LA TASA DE DESCOMPOSICIÓN, LA PÉRDIDA DE MASA Y LA LIBERACIÓN DE NUTRIENTES DE HOJARASCA SIMPLE Y MIXTA EN LA SABANA DEL NORTE DE GUINEA EN NIGERIA]

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SUMMARY

Background: This study presented a non-linear model to biologically describe the decomposition pattern, mass loss and nutrient release of four leaf litter species: *Khaya senegalensis* (African mahogany), *Mangifera indica* (Mango), *Gmelina arborea* (Beechwood), *Eucalyptus camaldulensis* (River red gum) and a mixture of the leaf litters using the standard litter bag technique. **Objective**: To explore different mathematical decomposition decay models in evaluating the decomposition rate and the relationship between mass loss and chemical parameters of some selected trees in Nigeria's northern Guinea savannah. **Methodology**: The experiment was a Completely Randomized Design with three replications. Fifteen litter bags were randomly placed in the field and retrieved at intervals of 0, 14, 28, 42, 56, 84, and 112 days (16 weeks). Three non-linear models were used to estimate the decomposition rate of the litter. Pearson correlation analysis was used to determine the relationship between mass loss and chemical composition. **Results**: Decomposition pattern gradually increased from 7 % up to 78.5 % by week 0 to 16 weeks. The leaf litter of *Mangifera indica* had the highest mass loss (62.9 %), followed by the litter mixture (44.0 %), *Eucalyptus camaldulensis* (43.6 %), *Gmelina arborea* (40.5 %) and *Khaya senegalensis* (39.3 %). Single exponential model (*Adj* R^2=93.25-98.59%), double exponential model (*Adj* R^2=87.93-98.98%), and three parameters asymptotic negative exponential model (*Adj* R^2=93.82-98.84%), described the decomposition process efficiently. Correlation analysis of mass loss and chemical composition was highly significant ($p \leq 0.05$), among all the leaf litter chemical properties, organic carbon, phosphorus, and nitrogen were the restraining factors. **Implication**: The mass loss was closely linked to the chemical properties of all the litter types. Among these properties, organic carbon and phosphorus were the limiting factors. **Conclusion**: We conclude that the single-leaf litter of *Mangifera indica* and *Khaya senegalensis* were superior in chemical composition, and decomposition than the mixed-leaf litter therefore they have the potential to enhancing soil fertility in the study area.
Key words: decomposition rate; exponential model; leaf litter; mass loss; soil fertility.

RESUMEN

Antecedentes: Este estudio presentó un modelo no lineal para describir biológicamente el patrón de descomposición, pérdida de masa y liberación de nutrientes de cuatro especies de hojarasca: *Khaya senegalensis* (caoba africana), *Mangifera indica* (Mango), *Gmelina arborea* (Haya), *Eucalyptus camaldulensis* (Goma roja de río) y una mezcla de hojarasca utilizando la técnica estándar de la bolsa de arena. **Objetivo**: Explorar diferentes modelos matemáticos de descomposición para evaluar la tasa de descomposición y la relación entre la pérdida de masa y los parámetros químicos de algunos árboles seleccionados en la sabana del norte de Guinea en Nigeria. **Metodología**: El experimento fue un Diseño Completamente Aleatorio con tres repeticiones. Se colocaron quince bolsas de basura en el campo y se recuperaron en intervalos de 0, 14, 28, 42, 56, 84 y 112 días (16 semanas). Se

† *Submitted April 18, 2024 – Accepted August 12, 2024. http://doi.org/10.56369/tsaes.5576*

ISSN: 1870-0462.
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utilizaron tres modelos no lineales para estimar la tasa de descomposición de la basura. Se utilizó el análisis de correlación de Pearson para determinar la relación entre la pérdida de masa y la composición química. **Resultados.** El patrón de descomposición aumentó gradualmente desde el 7 % hasta el 78.5 % entre las semanas 0 y 16. La hojarasca de *Mangifera indica* tuvo la mayor pérdida de masa (62.9 %), seguida de la mezcla de hojarasca (44,0 %), *Eucalyptus camaldulensis* (43,6 %), *Gmelina arborea* (40.5 %) y *Khaya senegalensis* (39.3 %). El modelo exponencial único (Adj R^2=93.25-98.59%), el modelo exponencial doble (Adj R^2=87.93-98.98%) y el modelo exponencial asintótico negativo de tres parámetros (Adj R^2=93.82-98.84%), describieron el proceso de descomposición de manera eficiente. El análisis de correlación de la pérdida de masa y la composición química fue altamente significativo ($p \leq 0.05$), entre todas las propiedades químicas de la hojarasca, el carbono orgánico, el fósforo y el nitrógeno fueron los factores restrictivos. **Implicaciones**: La pérdida de masa estuvo estrechamente relacionada con las propiedades químicas de todos los tipos de cama. Entre estas propiedades, el carbono orgánico y el fósforo fueron los factores limitantes. Conclusión: Concluimos que la hojarasca de una sola hoja de *Mangifera indica* y *Khaya senegalensis* fue superior en composición química y descomposición que la hojarasca mixta, por lo que tiene el potencial de mejorar la fertilidad del suelo en el área de estudio.
Palabras clave: tasa de descomposición; modelo exponencial; hojarasca; pérdida de masa; fertilidad del suelo.

INTRODUCTION

Leaf litter fall is pivotal in shaping the soil's physical, chemical, and biological attributes, influencing the overall productivity of an ecosystem. This is because the presence of leaf litter contributes to the improvement of both the quality and quantity of soil organic matter. Consequently, this improvement leads to enhanced soil quality by reducing bulk density and erosion, improving soil structure, increasing cation-exchange capacity, promoting infiltration, bolstering water holding capacity, and facilitating the retention of soil nutrients. (Bünemann *et al*., 2018; Quer *et al*., 2022). The breakdown of leaf litter serves as a crucial provider of both energy and nutrients for soil and litter organisms. Additionally, it plays a significant role in facilitating nutrient recycling within the plant community (Naik *et al*., 2018). Furthermore, the presence of leaf litter enhances biodiversity and stimulates the activity of soil microorganisms, essential for supporting plant productivity (Barrios *et al*., 2018). Generally, a rise in soil fertility correlates positively with the quality of leaf litter, nutrient concentrations in live leaf tissue, decomposition rates, and nitrogen mineralization (Kaba 2017; Xiao *et al*., 2019; Zhang *et al*., 2023). Litter decomposition is an important biogeochemical activity in forest ecosystems that influences carbon and nutrient cycle rates (Liao *et al*., 2022). One of the major processes that greatly influence nutrient cycling at the soil–plant interface are litter decomposition and nutrients released (Lin *et al*., 2019). The debris covering the floor of the forest functions as a system for inputting and outputting nutrients. The rates of both the descent and decomposition of forest litter play a crucial role in controlling nutrient cycling. Ren *et al*. (2018) discovered that the decomposition and nutrient release rates of residues are influenced by environmental factors like temperature and soil moisture, in addition to the biochemical content of plant materials.

According to Mahmood *et al*. (2014) and Zhu *et al*. (2010), the amount of nutrients added by litter decomposition varies by species. Similarly, the amount of nutrients provided to a given ecosystem changes depending on the species and other climatic factors that play a role in the biogeochemical cycling of nutrients (Duan *et al*., 2018; Lin *et al*., 2021). However, there is a lack of information regarding the litter decomposition rate and nutrient release of frequently planted tree species in the Northern Guinea Savannah Zone of Nigeria. Against this background, there is, therefore, the need to determine the variations of leaf litter decomposition rate and evaluate the feasibility of manufacturing organic fertilizer from the litter of four selected species (*Khaya senegalensis* (African mahogany), *Mangifera indica* (Mango), *Gmelina arborea* (Beechwood), *Eucalyptus camaldulensis* (River red gum)) and their mixture.

Unlike traditional farming methods that rely on chemical fertilizers, organic farming systems prioritize the management of soil organic matter to enhance crop production (Watson *et al*., 2002). Consequently, incorporating plant residues has emerged as a crucial strategy for improving soil fertility and promoting sustainable land use. Understanding the composition of leaf litter and its rate of decomposition is crucial for influencing soil physical, chemical, and biological properties. This knowledge is essential to maximize the positive impact of plant residue on enhancing soil quality in Africa. Additionally, it is important to align the nutrient release from residue decomposition with plant nutrient uptake patterns. This synchronization helps prevent the loss of available nutrients through leaching, runoff, and erosion. Thus, determining the best suitable plant material can contribute to improving the fertility of the soil and become an attractive investment in Sub-Saharan Africa. The objective of this study was to explore different mathematical decomposition decay models in evaluating the decomposition rate and the relationship between mass loss and chemical parameters of some selected trees found in the northern Guinea savannah of Nigeria. Based on this objective, experiments were conducted to validate this hypothesis – which decomposition model will give a better prediction of the decomposition rate, mass loss and different nutrient release pattern of three different types of leaves and their combinations in the study area.

MATERIALS AND METHODS

Description of the experimental site

The experiment was conducted in the year 2022 at the Institute for Agricultural Research, Ahmadu Bello University, Samaru, Zaria, Kaduna State, Northern Guinea Savannah zone of Nigeria field (IAR plot R14). The experimental area has a geo reference of latitude 110 10' 0" N and longitude 7^0 37' 60"E and an altitude of 688 m above sea level. This region is characterized by two distinct seasons: the dry season comprising the cold dry period also known as the harmattan (November-December) and the hot dry period (April-June) as well as a warm rainy season (July-September) with rainfall of about 1060 mm annually. October and March constitute traditional months between the rainy and cold dry seasons and between the hot dry period and the rainy season. Warm conditions and high relative humidity prevail during the rainy season. The region has lots of tree species which are characterized by leaf falls during the dry season and very high temperatures which affect plant growth and developmental process. The textural class of the soil is loam with a neutral pH of 7.35 in H_2O and 6.66 in $CaCl_2$ (Institute of Agricultural Research Metro station, 2021).

Summary of weather condition

Figure 1 shows the monthly summary of weather conditions in Samaru-Zaria through the year of study. Data collected revealed that, maximum temperature was recorded in May (36.9° C), followed by November (34.0° C). The average temperature throughout the study was 26.8 C, and radiation was average throughout the experiment (20-25 Bq). Rainfall increased from May (141 mm) through August (342 mm) down to October (49 mm). The total rainfall throughout the year of the study was (940.4 mm).

Leaf litter collection and chemical analysis of the samples before decomposition

Senescent (Fall) leaves of African mahogany (*Khaya senegalensis)*, Mango (*Mangifera indica*), Beechwood (*Gmelina arborea*), and River red gum (*Eucalyptus camaldulensis*) were picked from the selected tree species from the native forest of the Northern Guinea savannah and gathered separately. The gathered leaf litter specimens were meticulously cleansed using a gentle brush under flowing tap water, with a final rinse in distilled water. Subsequently, each sample was left to air-dry in the shade at the Department of Soil Science Laboratory. Air-dried leaf litter samples were ground in a mortar and sieved through a 1 mm mesh size laboratory sieve. The fine powder was used for the chemical analysis before decomposition using standard procedures. Organic carbon (OC) was determined by igniting the samples at 550 °C using the Walkley and Black procedure as reviewed by (Okalebo *et al*., 2002). Total nitrogen (TN) content in leaf litter was analyzed by digesting 0.1 g of samples

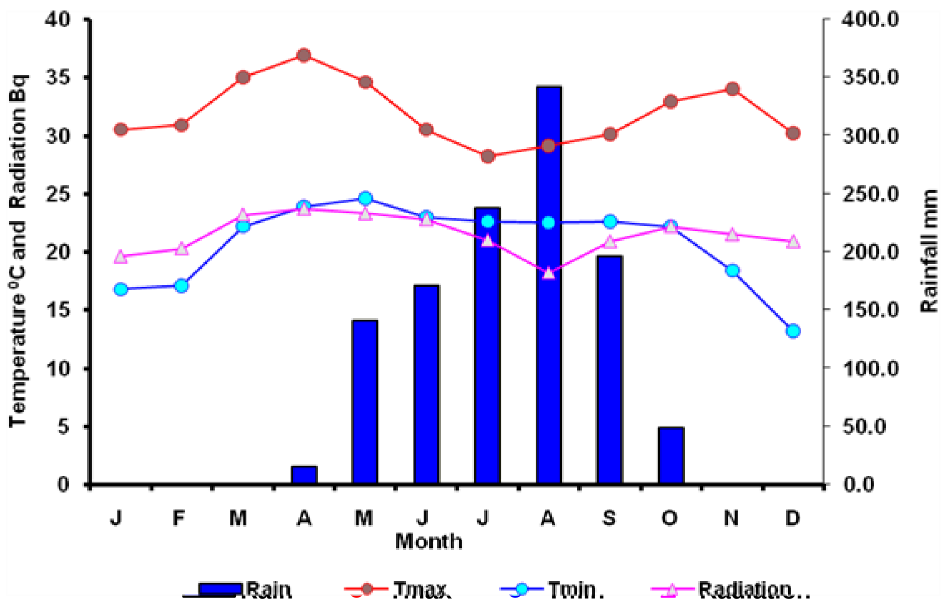

Figure 1. Monthly weather summary at Samaru-Zaria through study (Elaborated using data from IAR).

in a 5 ml solution of concentrated sulfuric acid, using a digestion mixture consisting of sodium sulfate and copper sulfate in a 10:4 ratio. The nitrogen in the digest was quantified using Kjeldhal's method, as outlined by Saez-Plaza *et al*. (2013). Additionally, the total phosphorus (TP) content was determined through the chlorostannus reduced molybdophosphoric blue color method in a sulfuric acid system (Bray and Kurtz, 1945). The color intensity was measured at 660 nm using a UV spectrophotometer.by digesting 0.1 g of samples in 5 ml of concentrated sulphuric acid using a digestion mixture (sodium sulfate: copper sulfate in 10:4 ratio) and nitrogen in the digest was determined by Kjeldhal's method as reviewed by Saez-Plaza *et al*., (2013). Total phosphorus (TP) content by following chlorostannus reduced molybdophosphoric blue colour method in the sulphuric acid system (Bray and Kurtz, 1945) and the color intensity was read at 660 nm in a UV spectrophotometer. Total potassium (TK), and sodium (Na) were determined using flame photometry and Atomic Absorption Spectrophotometer (AAS) as appropriate after wet digestion (Anderson *et al*., 2017). The Follin-Ciocalteu's method (Moyer *et al*., 2002) was employed to ascertain the overall polyphenol content while lignin content was determined through acid detergent fiber (ADF) via Ankom technology as described by Okalebo *et al*. (2002).

Decomposition studies of leaf litters

Litter bags of 2 mm nylon mesh containing around 10 grams of air-dried leaf litter from a specific species or a blend of multiple species. (Tarfa, 2001; Mohammed, 2013) were fastened to the soil with a wooden stick of about 15 cm long. In all, 90 litter bags (5 litter types x 3 replications x 6 retrievals) were placed in the field. Litter bags were retrieved and sampled at intervals of 0, 14, 28, 42, 56, 84, and 112 days.

During each sampling period, three replicate litter bags of each litter were collected. Samples were delicately washed under a slow stream of tap water, followed by a rinse with distilled water. Afterward, they were oven-dried at 65°C for 48 hours and then weighed to ascertain mass loss. (Naik *et al*., 2018). Litter breakdown and nutrient release were quantified in terms of dry matter (DM) loss and the percentage of nutrient release per recovery, as indicated by Asigbaase *et al*. (2021). The selection of mesh size aimed to enhance organism access to the litter while minimizing particle loss, as explained by Karberg *et al*. (2008).

Non-linear models for estimating the decomposition rate of litter

Mass loss percentage (%) is the rate of litter loss to the soil and it was expressed in percentage using the Olsen (1963) model.

Mass loss (%) = initial mass (g) - final mass (g)/initial mass (g) x 100 (1)

Where; initial mass is the weight at sampling time and final weight is after oven drying at 65ºC.

Exponential decay models used in estimating the decomposition rate of litter

Single exponential decay model

The decay model proposed by Olson (1963) was employed to estimate the decomposition constant (k) for leaf litter. In this model, 'M0' represents the initial mass of litter, 'M1' is the mass of litter remaining after time 't', 'ln' denotes the natural logarithm, 't' represents time in days, and 'k' signifies the decomposition rate in days. The time intervals for achieving 50% and 95% mass loss were determined as $t_{50\%} = 0.693/k$ and $t_{95\%} = 3/k$, respectively while the formula proposed by Olson (1963) was utilized to determine the decay rate coefficient for constant potential weight loss.

$$X/X^0 = e^{-kt} \quad (2)$$

The standard equation (Bockheim *et al*., 1991) was employed to estimate the half-life ($t_{0.5}$) of decomposing litter based on k values.

$$t_{(0.05)} = \text{In}(0.5)/\text{-}k = -0.693/\text{-}k \quad (3)$$

Double exponential decay model of Hunt (1977):

$$\frac{w_t}{w_o} = Ae^{-k1t} + (1 - A)e^{-k2t} \quad (4)$$

Where Wt is the amount of mass remaining at time t; Wo is the mass at time zero; A and (1 – A) are the labile and recalcitrant fractions of the organic material; k_1 and k_2 are the decay constant at the 1st (labile fraction) and 2nd (recalcitrant fraction) compartments respectively.

Asymptotic negative exponential decay model (Weider *et al*., 1983)

$$\frac{w_t}{w_o} = \text{Ca} + (1 - Ca)e^{-kt} \quad (5)$$

Where Ca and (1 – Ca) represent the labile and the recalcitrant fractions respectively. The asymptotic model represents a variation of both the single- and double-exponential models. In this model, the trend approaches a positive constant instead of zero, as seen in the single-exponential model. Additionally, the unyielding fraction remains entirely resistant to decay, denoted by $k_2 = 0$, unlike the double-exponential model.

Statistical Analysis

The decomposition pattern in relation to leaf litter was examined through a one-way analysis of variance (ANOVA) conducted using the R car package (version 3.0-2) developed by Fox and Weisberg (2011). This analysis aimed to assess the fixed effect of various leaf litter types on the decomposition process. To discern significant differences, Tukey's test (α = 0.05) was applied for multiple comparisons using the R least square means package (version 2.30-0) by Length (2016), along with the R multicomp package (version 1.4-10) by Hothorn *et al*. (2008). A non-linear regression package was used to fit the decomposition curves. We further explored the relationships between the mass loss and various chemical compositions of leaf litter through correlation analysis. Employing the cor.test function in R, we calculated Pearson's correlation coefficients and determined p-values at significance levels of 0.001, 0.01, and 0.05 to evaluate the statistical significance of the observed correlations. The correlation analysis was displayed using R package corrplot v0.92 (Wei and Viliam, 2021).

RESULTS

Chemical composition of leaf litter prior decomposition process

The chemical composition of the leaf litter is shown in Table 1. The litter of *Eucalyptus camaldulensis* had the highest concentration of organic carbon, followed by mixed litter, *Khaya senegalensis*, and *Gmelina arborea* while *Mangifera indica* recorded the least concentration of organic carbon in the leaf litters. The litter of *Gmelina arborea* recorded the highest total nitrogen concentration while *Khaya senegalensis* had the least nitrogen concentration in the leaf litter. The litter of *Gmelina arborea* showed the highest concentration of total phosphorus and potassium in the leaf litter. The litter of *Eucalyptus camaldulensis* recorded the highest value of 33.3 for C: N while *Gmelina arborea* had the least value of 20.6. Lignin concentration was lowest in the litter of *Gmelina arborea* while combined leaf litters recorded the highest concentrations. Total polyphenol content was highest in *Mangifera indica* and lowest in *Eucalyptus camaldulensis*.

Litter decomposition pattern

Table 2 shows the effects of leaf litter types, weeks of sampling, and their interaction on the decomposition pattern. Significant variations ($p < 0.05$) were observed in the decomposition patterns among the different treatments. The litters of *Khaya senegalensis* and *Gmelina arborea* had the highest final weight which differed significantly ($p<0.05$) from other leaf litters. The litter of *Mangifera indica* recorded the lowest final weight (3.71 kg). The litter of *Mangifera indica* had the highest mass loss (62.9%), followed by mixed, *Eucalyptus camaldulensis*, *Gmelina arborea*, and *Khaya senegalensis*. The mass loss pattern gradually increased from week 0 (7.0%) up to 16 weeks (78.5%). The ANOVA results showed that litter types, sampling periods, and the interaction between the two treatments were significant for both the final weight and the mass loss.

Models estimations of decomposition

The single exponential model of decomposition rate at constant *k* and the time to 50% decomposition among the leaf litter are shown in Table 3. The decomposition of *Mangifera indica* litter was approximated to be nearly complete, reaching a limit value of 98.2%, while mixed litters recorded a decomposition rate of 77.9%, *Gmelina arborea* (67.8%), *Khaya senegalensis* (67.6%) and *Eucalyptus camaldulensis* (60.6%). The litter of *Mangifera indica* had the fastest decay rate constant (9.84), followed by mixed, *Gmelina arborea*, and *Khaya senegalensis*, while *Eucalyptus camaldulensis* had the lowest decay rate constant (1.07) over 112 days of decomposition. The half-life of decomposing litter of *Eucalyptus camaldulensis, Mangifera indica*, *Gmelina arborea* and mixed were 0.65, 0.18, 0.19 and 0.14 respectively. *Khaya senegalensis* with 0.07 half-life of decomposition had a shorter duration. The period to attain 95% and 99% final level of decomposition was longer in the litters of *Eucalyptus camaldulensis.* The coefficient of determination and adjusted coefficient of determination had similar estimates for all the leaf litter. The litters of *Gmelina arborea* had the highest prediction response rate (*Adj* R^2=98.59%) while *Khaya senegalensis* recorded the least (*Adj* R^2=93.25%), though the Olson model showed a good fit for all the leaf litters. In Figure 2, the litter of *Mangifera indica* differed significantly ($p<0.05$) from other varieties of agroforestry leaf litter in the litter mass remaining and showed huge perturbations during the decomposition process. There were also notable differences in the rate of decomposition over time among the leaf litter.

The double exponential model describe the decomposition process accurately as shown in Table 4 with a good fit among the leaf litters (*Khaya senegalensis*, 97.32%- 98.98; *Gmelina arborea*), except *Mangifera indica* (Adj R^2=87.93%). The mixed leaf litters had the highest labile fractions (94.22), followed by *Gmelina arborea* and *Mangifera indica* while *Khaya senegalensis* and *Eucalyptus camaldulensis* recorded the lowest labile fractions. Figure 3, shows that there were differences in apparent rate of decomposition change through time. The litter of *Mangifera indica* showed a slower decomposition rate as compared to other varieties of leaf litter.

Table 1. Chemical composition of leaf litter prior decomposition process (g kg^{-1}).

Properties	*Khaya Senegalensis*	*Mangifera indica*	*Gmelina Arborea*	*Eucalyptus Camaldulensis*	Mixed
Organic Carbon	333.2	306.1	323.4	409	341.4
Total Nitrogen	10.5	12.2	15.7	12.3	12.8
Total Phosphorus	1.7	1.7	2.0	1.4	1.7
Potassium	3.0	3.7	4.8	4.5	4.0
C: N	31.7	25.1	20.6	33.3	26.8
Total Polyphenol	111.4	130.9	86.6	77.5	101.4
Lignin	150.1	180	92.7	122.1	136.7

Table 2. Effects of leaf litter types and sampling periods on the decomposition pattern.

Treatment	Initial weight (g)	Final weight (g)	Mass loss (%)
Litter types (LT)			
Khaya senegalensis	10.00	6.07[a]	39.30[c]
Gmelina arborea	10.00	5.95[a]	40.54[c]
Mangifera indica	10.00	3.71[c]	62.91[a]
Eucalyptus camaldulensis	10.00	5.64[b]	43.62[b]
Mixed	10.00	5.60[b]	44. 00[b]
SE±		0.075	0.601
Sampling Periods (SP) (Weeks)			
0	10.00	9.30[a]	7.00[g]
14	10.00	7.70[b]	23.01[f]
28	10.00	6.33[c]	36.70[e]
42	10.00	4.99[d]	50.02[d]
56	10.00	4.27[e]	57.30[c]
84	10.00	3.03[f]	69.74[b]
112	10.00	2.15[g]	78.52[a]
SE±		0.089	0.932
Interaction			
Litter types (LT)		**	**
Sampling periods (SP)		**	**
LT x SP		**	**

Means followed by similar letters under the same column are not significantly different at p= 0.05 according to Tukey's HSD. SE = standard error of mean, **= highly significant at 1 % level of probability

Table 3. Single exponential model decomposition rate at constant (k) and the time to 50% decomposition among leaf litters.

Treatment	*k*	t(0.5)	*3/k*	*5/k*	R^2	*Adj* R^2
Khaya senegalensis	3.64	0.07	0.83	1.37	93.25	93.25
Mangifera indica	9.84	0.18	0.31	0.51	98.07	98.07
Gmelina arborea	3.90	0.19	0.77	1.28	98.59	98.59
Eucalyptus camaldulensis	1.07	0.65	2.81	4.69	93.74	93.74
Mixed	4.83	0.14	0.62	1.04	98.35	98.35

t (0.5) = Half-life of decomposing litter; *k* = decay rate coefficient ($112days^{-1}$); R^2 = Coefficient of determination; *Adj* R^2=adjusted Coefficient of determination; 3/k = period to attain 95% of the final level; 5/k = time to reach 99% of the final level.

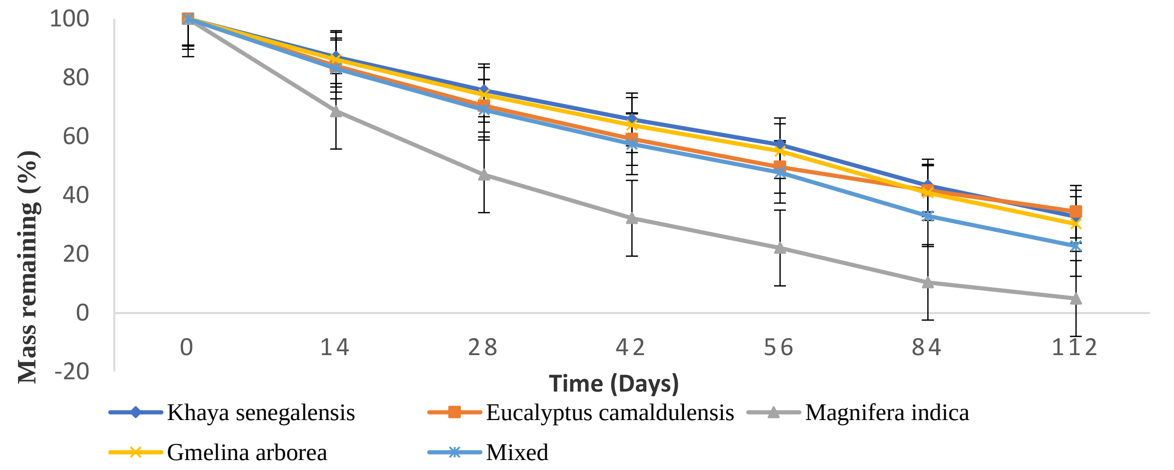

Figure 2. Litter mass remaining at different periods during decomposition as predicted by the single exponential model.

Table 4. Double exponential model of decomposition rate at constant (k) and parameter estimates among leaf litters.

Treatment	A	k_1	I-A	k_2	R^2	*Adj* R^2
Khaya senegalensis	24.43	3.71	76.72	3.71	98.66	97.32
Mangifera indica	67.36	10.52	39.92	10.52	93.97	87.93
Gmelina arborea	90.62	3.27	9.46	42.92	99.29	98.98
Eucalyptus camaldulensis	26.70	5.85	73.34	0.60	99.44	98.88
Mixed	94.22	4.45	6.21	27.65	98.52	97.04

A and (1 – A) are the labile and recalcitrant fraction of the organic material; k_1 and k_2 (112 days-^{1}) are the decay constant at the 1st (labile fraction) and 2nd (recalcitrant fraction) compartments respectively. R^2=Coefficient of determination; *Adj* R^2=adjusted Coefficient of determination. T=time in days

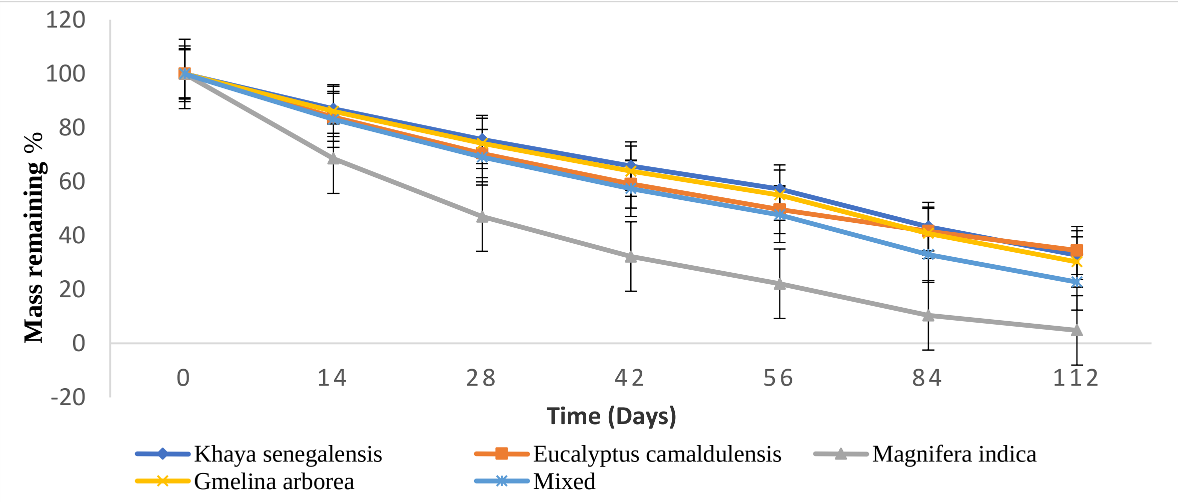

Figure 3. Litter mass remaining at different periods during decomposition as predicted by the double exponential model.

Table 5 shows the asymptotic negative exponential model of decomposition rate at constant k and parameter estimates among the leaf litter. The responses of the asymptotic model in describing the decomposition were all good which ranged from 93.82% in *Mangifera indica* through 98.84% in the litter of *Eucalyptus camaldulensis.* The decay rate coefficient was higher in the litter of *Mangifera indica*, followed by mixed litters, *Gmelina arborea*, *and Khaya senegalensis* while *Eucalyptus camaldulensis* had a slower decay rate coefficient over 112 days of decomposition. *Mangifera indica* had the highest values for labile and recalcitrant fractions while *Eucalyptus camaldulensis* recorded the least. Figure 4 shows the decomposed mass at different periods as predicted by asymptotic negative exponential model.

Table 5. Asymptotic model of decomposition rate at constant (k) and parameter estimates among leaf litters.

Treatment	*Ko*	A	R^2	*Adj* R^2
Khaya senegalensis	353.08	106.63	98.63	98.35
Mangifera indica	855.04	116.71	94.85	93.82
Gmelina arborea	448.07	80.92	98.85	98.62
Eucalyptus camaldulensis	159.70	63.24	99.03	98.84
Mixed	497.13	95.77	98.39	98.06

A represent the recalcitrant fractions respectively; *ko* =decay rate coefficient (112days^{-1}); R^2=Coefficient of determination; *Adj* R^2=adjusted Coefficient of determination.

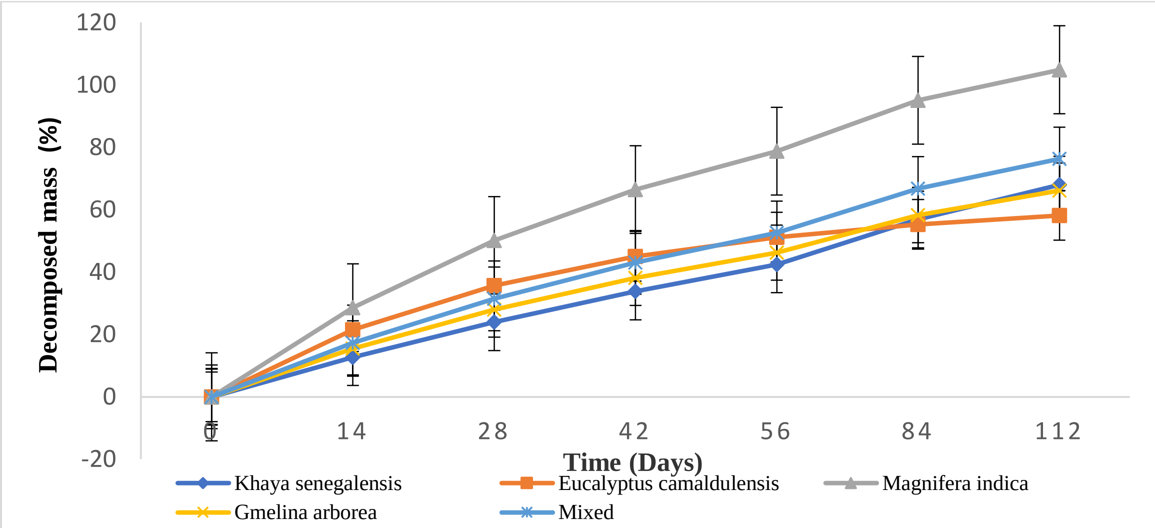

Figure 4. Decomposed mass at different periods as predicted by asymptotic negative exponential model

Correlation analysis of Mass loss and chemical composition of samples after decomposition

Figure 5 shows the relationship between mass loss and chemical composition in a litter of *Khaya senegalensis* (Panel A). Mass loss was significant and positively correlated with organic carbon (r=0.87; p<0.001), C:N (r=0.7; p<0.001), phosphorus (r=0.50; p<0.001), lignin (r=0.33; p<0.05). Mass loss showed significant negative correlations between nitrogen (r=-0.5; p<0.001) and potassium (r=-0.65; p<0.001). In the leaf litter of *Gmelina arborea* (Panel B), mass loss was highly significant (p<0.05) and positively correlated with organic carbon, lignin, total polyphenol content, and C: N ratio. Phosphorus, nitrogen and potassium were negative and strongly associated with mass loss (r=-0.8; p<0.001; r=-0.99; p<0.001 and k=-0.99; p<0.001).

In *Mangifera Indica* (C), the mass loss had a high, positive and significant relationship with phosphorus potassium (r=0.97; p<0.001) and total polyphenol content (r=0.89; p<0.001) in the leaf litter. Panel D reveals that mass loss had a positive strong relationship with phosphorus, lignin, C: N ratio and total polyphenol content in the leaf litter of *Eucalyptus Camaldulensis*. The correlation analysis of mass loss and chemical composition in mixed leaf litters are shown in Panel E. Mass loss had a strong significant and positive relationship with phosphorus (r=0.87; p<0.001), lignin (r=0.93; p<0.001) and C:N (r=0.78; p<0.001). Notable significant and negative correlations were observed between mass loss and nitrogen (r=-0.96; p<0.001), potassium (r=-0.5; p<0.001), total polyphenol content (r=-0.87; p<0.001) and organic carbon (r=-0.69; p<0.001).

DISCUSSION

The C/N ratio is a distinguishing characteristic of organic substrates. The high C to N ratio (33.3) observed in *Eucalyptus camaldulensis* in this study implies poor rates of decomposition and mineralization, thus resulting in inefficient cycling macronutrients such as nitrogen and phosphorus Ruwanza *et al*., (2014). This aligns with the findings in the report of Castro-Diez *et al*. (2011) who found a higher organic carbon-to-nitrogen ratio (84) in plant litter of *Eucalyptus spp* on the forest floor than in planted species (35). The C to N ratios in *Gmelina arborea* and *Mangifera indica* are below and equal to 20.6 and 25.1 respectively in this study which

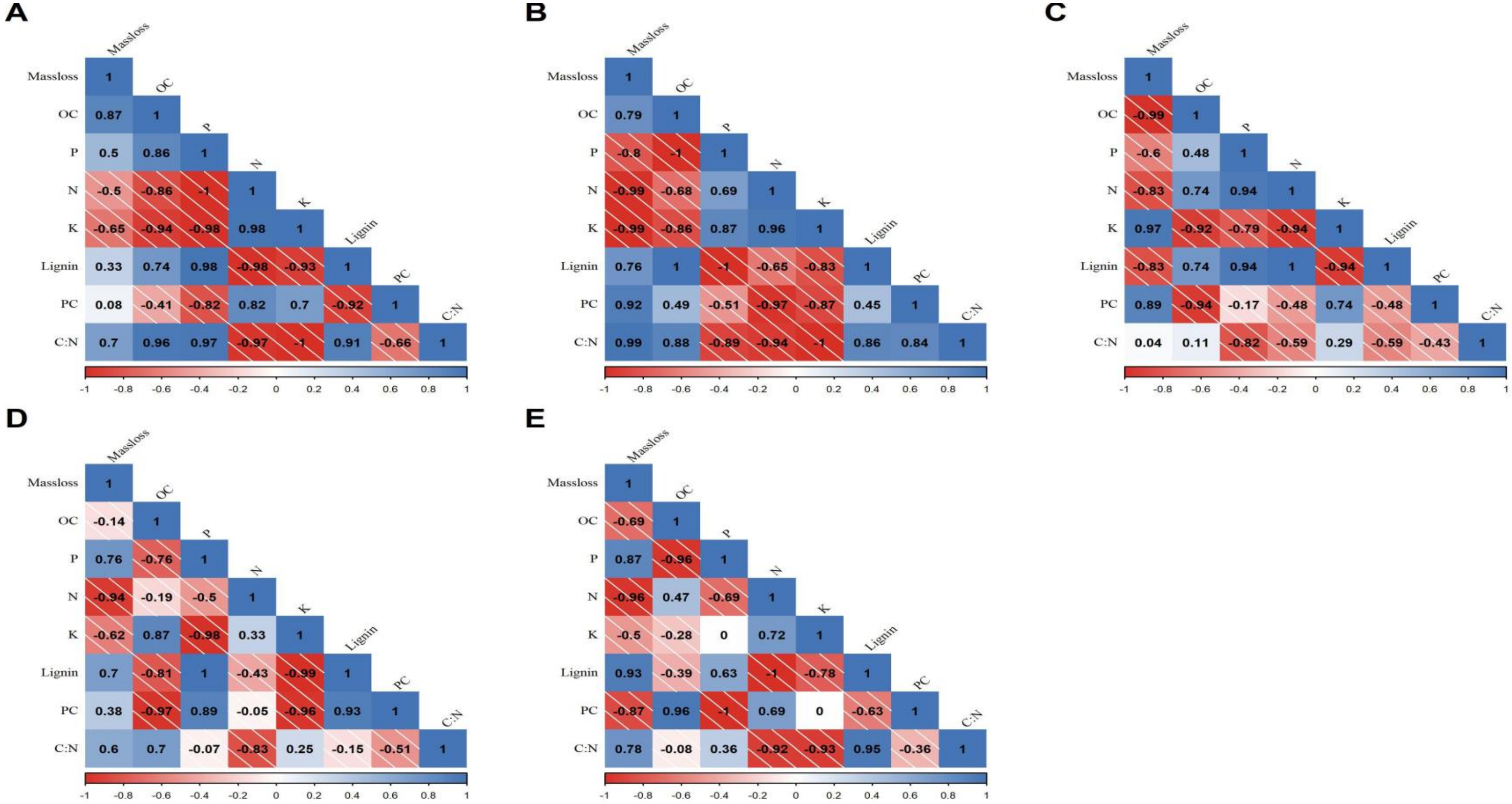

Figure 5. Correlation heatmap analysis of mass loss and chemical composition in PANEL A (*Khaya senegalensis*), PANEL B (*Gmelina arborea*), PANEL C (*Mangifera indica*). PANEL D (*Eucalyptus camaldulensis*), and PANEL E (MIXED); ***=highly significant (p<0.01); *=significant (p<0.05); OC=Organic carbon, N=total nitrogen, P= total phosphorus, K= potassium, PC= Total polyphenol content, C: N= carbon to nitrogen ratio.*

implies high-quality litter and has a tendency to decompose faster as a result of the release of easily soluble substances and non-lignified carbohydrates (Kaba, 2017; Naik *et al.*, 2018). The C to N ratios (20.6 -33.3) reported in this study for the leaf litter species is comparable to the 31.6 ± 2.7 ratio observed in 30-year-old cocoa systems, yet less than the 42.9 ± 1.5 ratio documented in 15-year-old cocoa systems by Dawoe *et al*. (2010) which suggests that the decomposition of leaf litter chemistry or quality played a partial role in its regulation.

The fluctuations in nutrient levels within leaf litter types could be correlated with soil and climatic factors, specifically temperature and humidity, soil nutrient composition and accessibility, vegetation or plantation age, and management practices (Kaba 2017; Naik *et al*., 2018).

The higher level of recalcitrant compounds of lignin and polyphenols in this research aligns with Dawoe *et al*. (2010) findings in Ghana, which documented elevated levels of recalcitrant compounds, specifically lignin and polyphenols, in cocoa leaves compared to shade tree leaves. Blanco and Aguilar (2015) observed that the litter layer significantly affects the primary soil erodibility factor, underscoring the pivotal role of the litter as the foremost soil protection agent in controlling erosion, therefore litters of *Khaya senegalensis* and *Mangifera Indica* in this study with higher lignin and polyphenols can serve as a major source of erosion control. Furthermore, the accumulation of litter will act as a significant contributor to soil organic matter upon decomposition. This factor plays a crucial role in shaping soil structure and enhancing soil stability and porosity. Simultaneously, it augments water infiltration capacity into the soil and effectively regulates soil erosion rates, as indicated by studies conducted by Singh *et al*. (2014), Certini *et al*. (2015), and Novara *et al*. (2015).

The decomposition of leaf litter in this study followed this pattern (*Mangifera indica*> mixed >*Gmelina arborea*> Kh*aya senegalensis*> *Eucalyptus camaldulensis*). The variation can be ascribed to distinctions in the initial nutrient concentration, their ratios, and the proportion of recalcitrant compounds present among various leaf litter species. Litter decomposition is influenced by litter quality, interacting environment, chemical and biological factors (Liu *et al*., 2010). The initial gradual reduction in litter mass during the first four weeks of decomposition in this investigation was attributed to the influence of inhibitory compounds like lignin, polyphenols, and prevailing climatic conditions. Across various timeframes and environmental settings, climatic factors such as moisture, temperature, and soil conditions exerted a more significant impact on decomposer activity compared to the quality of the litter, as noted by Vitousek *et al*. (1994). The observed variations in litter decomposition rates in this study can be attributed to the regulation of decomposition rates by the physical and chemical conditions within climatic and soil complexes.

In this investigation, the reduction in leaf litter mass conformed to an exponential decay model. This model indicates that the decomposition rate progressively diminishes as the duration following litter installation increases, a trend observed in numerous other research studies. (Kaba, 2017; Mohammed *et al*., 2019). The initial swift decline in mass in this investigation can be ascribed to the breakdown of easily soluble substances, non-lignified carbohydrates, and other easily degradable fractions, as documented in other studies (Dawoe *et al*., 2010; Triadiati *et al*., 2011). The affirmation that 30–50% of leaf biomass decomposes in the initial 3–4 months in tropical agroforestry and plantation systems (Kumar 2008) is substantiated by our findings, with over 30% of leaf biomass being lost during this timeframe. The gradual reduction in mass during the later stages of this study is likely associated with the accumulation of resistant fractions like lignin and cellulose in leaf litter as decomposition advances, as affirmed by Naik *et al*. (2018).

Mass loss of leaf litter was rapid during the first six (6) weeks of decomposition relative to later periods in this study. This aligns with the observations made by Berg and Staaf (1981), indicating that during the initial phases of leaf decomposition, the initial loss primarily involves small soluble carbon molecules such as starches and amino acids. This results in the retention of more resistant molecules, like lignin. As a result, the decomposition process over six weeks occurs swiftly, driven by the ease of breaking down the energy-rich small soluble carbon molecules present in the leaf litter. In litterbag field experiments, the current mass loss rate constants of the litterbags were within the range of those previously published (Domínguez *et al*., 2014; Lori *et al*., 2017).

Olson (1963), set values of above 1.00 for high rates of decomposition, the decomposition *k* values by the single exponential model in this study range from (1.0661-9.8421). The decay rate coefficient (k = 1.0661-9.8421) documented in this study for leaf litter species falls within the range of coefficients estimated for Indonesian natural forests during the wet period (k = 1.87) (Triadiati *et al*., 2011) and secondary forests in eastern Amazon (k = 1.2 –1.9) (Hayashi *et al*., 2012). Furthermore, the decay rate coefficient (k = 1.0661-9.8421) reported in this study exceeds the value of 0.46 observed in cocoa agroforestry systems in Brazil (Fontes *et al*., 2014).

Podong *et al*. (2013) documented a carbon density of 0.15 for secondary mixed deciduous forests in Northern Thailand, while Dawoe *et al*. (2010) reported a value of 0.35 for secondary forests in the Ashanti region of Ghana.

The elevated decomposition coefficient noted in this study for *Mangifera indica* (9.821) may be attributed to an increased concentration of phosphorus found in the leaf litter. This higher phosphorus content is likely to impact the composition and functioning of decomposer communities (Domínguez *et al.*, 2014; Lori *et al.*, 2017). The quality of litter not only influences the makeup of the decomposer community and the pace of decomposer activity but also plays a role in either enhancing or suppressing the palatability of detrivore animals and soil microbial activity. In this investigation, *Gmelina arborea* litter, characterized by elevated nitrogen (N) concentration, exhibited a slower decomposition rate compared to the mixed litter of *Mangifera indica*, *Khaya senegalensis*, and *Eucalyptus camaldulensis*. Despite the high N concentration, microbial activity was not hindered, indicating that nitrogen was not a limiting factor under these conditions. Therefore, the nitrogen concentration in litter showed a significant correlation with the subsequent rate of decomposition.

The dynamic of the single exponential, double exponential, and asymptotic decay models exhibits efficient and robust curvature, implying that the seasonal cycle adequately accounts for variations in the decomposition process. Several factors could contribute to this pattern, such as the necessity for an initial phase of microbial colonization preceding the commencement of the decomposition process. This rationale has been previously cited to clarify the sigmoidal-type increase observed in the decomposition pattern. However, when examining litter decomposition, researchers frequently observe dynamics with a pronounced curvature that cannot be adequately represented by a single-exponential equation. This phenomenon is attributed to variations in the decomposition process, where certain components, such as carbohydrates, hemicelluloses, and water-soluble compounds, degrade more rapidly, while others, including waxes, lignin, and suberins, persist for a longer duration (Berg *et al*., 2010). As the former disappears and the latter accumulates, k decreases. Study by Aber *et al.* (1990) on litter bags indicated a consistent decomposition rate that has been observed until approximately 80% of the accumulated mass is lost.

On the contrary, various types of foliar litter exhibit a faster initial decomposition, followed by a declining rate in later stages as the litter undergoes aging. This reduction in decomposition rate can occur gradually or rapidly, giving rise to distinct patterns as evident in the limit values documented in this research. Given the considerable range in reported limit values, we can consider their numerical representation as a continuum, spanning from 42% to 100%, signifying complete decomposition. The limit values in this study ranged from 98.2% in *Mangifera indica* to 60.6% in *Eucalyptus camaldulensis* which was higher than the 42% accumulated mass loss reported by Berg *et al.* (2010). Alternative findings indicate upper limits reaching 100% (Berg and Ekbohm, 1993; Berg *et al*., 2010). The possibility of a limit surpassing 100% and carrying significance is attributed to the numerical inputs affecting the function, signifying complete decomposition leading to the 100% threshold. Notably, substantial variations in limit values exist even within a genus and specific litter species, contributing to a notable diversity in patterns (Berg *et al*., 2010). The variations in the parameter k between our investigation and the studies mentioned earlier could be attributed to distinctions in climatic and soil conditions, as well as differences in litter chemistry.

In *Khaya senegalensis* and *Mangifera indica* litters, mass loss was strongly and negatively correlated with organic carbon which implies that an increase in mass loss will cause a significant reduction in organic carbon which agrees with the observations of several studies (Aber *et al*., 1990; Berg and McClaugherty, 2014). Judging from the negative correlation between mass loss and organic carbon, Mass loss could be reliably forecasted by the presence of organic carbon in litter of *Khaya senegalensis* and *Mangifera indica*. In *Gmelina arborea*, an increase in mass loss will significantly cause a reduction in phosphorus and potassium, this agrees with the trend as reported by (Berg and McClaugherty, 2014) that microbes often have enough relationship with phosphorus. In *Eucalyptus camaldulensis*, mass loss was highly and negatively correlated with phosphorus and organic carbon. This implies that an increase in mass loss will lead to a significant decrease in organic carbon. Based on the inverse associations observed between mass loss and potassium as well as organic carbon, it suggests a reliable predictability for the mass loss of *Eucalyptus camaldulensis* litter. This aligns with the correlation pattern found in hardwood leaf litter (Taylor *et al*., 1989) and in native tree species cultivated in a coal mine in India (Singh *et al*., 1999).

CONCLUSION

The single-leaf litter types were superior in chemical composition, and decomposition to the mixed leaf litter types. Olsen model (*Adj* R^2=93.25-98.59%), double exponential (*Adj* R^2=87.93-

98.98%), and three parameters asymptotic negative exponential model (*Adj R^2=93.82-98.84%)* were parsimonious and describe the decomposition process efficiently. Mass loss had a strong relationship with the chemical properties of all the litter types. Among all litter chemical properties organic carbon and phosphorus, were the restraining factors. *Mangifera indica* is the best litter species to use based on nutrient return through leaf litter decomposition followed by *Khaya senegalensis* and mixed leaf litters. There is a great potential for leaf litters of *Mangifera indica*, *Khaya senegalensis,* and mixed for soil fertility improvement. However, more research should be conducted on this leaf litter to assess its long-term and sustainable effect on the physicochemical properties of the soil and crop yield.

Acknowledgments
We thank the management of the Department of Soil Science, Ahmadu Bello University, Zaria for assisting in finding appropriate study sites. Special thanks also goes to all the staff of Soil Science Laboratory who assisted in carrying out all the laboratory analyses.

Funding. The research was not funded by any organization.

Conflict of Interest statement. The authors have declared that they have no known potential conflicts of interest, competing financial interests or personal relationships before, during and after this study that could have appeared to influence the work reported in this paper.

Compliance with ethical standards. This paper is an original contribution that has not been submitted to any other journal for publication and it does not require approval by a bioethical committee.

Data Availability. Data will be made publicly available or by contacting authors directly.

Authors contribution statement (CRediT). I.Y. Amapu – Conceptualization, Supervision. **F.A. Akinsola –** Methodology, Writin – original draft. **E.Y. Oyinlola -** Investigation, Project administration. **M. Drame -** Investigation, Data curation, Formal analysis. **C.M. Aboyeji –** Visualization, Writing – review and editing.

REFERENCES

Aber, J.D., Melillo, J.M. and McClaugherty, C.A., 1990. Predicting long-term patterns of mass loss, nitrogen dynamics, and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. *Canadian Journal of Botany*; 68, pp. 2201-2208. https://doi.org/10.1139/b90-287

Aerts, R. and Caluwe, H., 1997. Nutritional and plant-mediated controls on leaf litter decomposition of *Carex species*. *Ecology*, 78(1), pp. 244-260. https://doi.org/10.2307/2265993

Ahlam, A.M., 2004. Assessment of rate of decomposition and nutrient release from leaf residue of some tree species. *M.Sc. Thesis in Desertification and Desert Cultivation, University of Khartoum, Sudan.*

Anderson, C., Peterson, M. and Curtin, D., 2017. Base cations, KC and Ca2C, have contrasting effects on soil carbon, nitrogen and denitrification dynamics as pH rises. *Soil Biology and Biochemistry*, 113, pp. 99-107. https://doi.org/10.2136/vzj2017.08.0155

Asigbaase, M., Dawoe, E., Sjogerstan, S. and Lomax, B.H., 2021. Decompositon and nutrient mineralization of leaf litter in smallholder cocoa agroforest: a comparison of organic and conventional farms in Ghana. *Journal of Soil and Sediments,* 21, pp. 1010-1023. https://doi.org/10.1007/s11368-020-02871-6

Barrios, E., Valencia, V., Jonsson, M., Brauman, A., Hairiah, K., Mortimer, P.E., and Okubo, S., 2018. Contribution of trees to the conservation of biodiversity and ecosystem services in agricultural landscapes. *International Journal of Biodiversity of Science and Ecosystem Service Management,* 14, pp.1–16. https://doi.org/10.1080/21513732.2017.1399167

Berg, B., and McClaugherty, C., 2014. *Plant Litter. Decomposition, Humus Formation, Carbon Sequestration*, 3rd ed. Springer Verlag, Heidelberg, Berlin, pp. 317. https://doi.org/10.1007/978-3-662-05349-2

Berg, B., De Marco, A., Davey, M., Emmett, B., Hobbie, S., Liu, C., McClaugherty, C., Norell, L., Johansson, M.-B., Rutigliano, F., Vesterdal, L. and Virzo De Santo, A., 2010. Limit values for foliar litter decomposition in pine forests. *Biogeochemistry,* 100, pp. 57-73.

https://doi.org/10.1007/s10533-009-9392-4

Berg, B., and Ekbohm, G., 1993. Decomposing needle litter in lodgepole pine (*Pinus contorta*) and Scots pine (*Pinus sylvestris*) monocultural systems. Is there a maximum mass loss? *Scandinavian Journal of Forest Research*, 8, pp. 457-465. https://doi.org/10.1080/02827589309382780.

Berg, B. and Staaf, H., 1981. Leaching, accumulation and release of nitrogen in decomposing forest litter. *Ecological Bulletins*, 33, pp. 163-78. https://www.jstor.org/stable/45128659

Blanco, R. and Aguilar, A., 2015. Soil erosion and erosion thresholds in an agroforestry system of coffee (*Coffea arabica*) and mixed shade trees (*Inga* spp. and *Musa* spp.) in Northern Nicaragua *Agriculture Ecosystems and Environment*, 210, pp. 25-35. https://doi.org/10.1016/j.agee.2015.04.032

Bockheim, J.G., Jepsen, E.A., and Heisey, D.M., 1991. Nutrient dynamics in decomposing leaf litter of four tree species on a sandy soil in northwestern Wisconsin. *Canadian Journal of Forest Research*, 21(6), pp. 803-812. https://doi.org/10.1139/x91-113

Bray, R.H. and Kurtz, L., 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science;* 59(1), pp. 39-46. https://doi.org/10.1097/00010694-194501000-00006

Bünemann, E.K, Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G. and de Goede, R., 2018. Soil quality – a critical review. *Soil Biology and Biochemistry*, 120, pp. 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Castro-Díez P., Fierro-Brunnenmeister N., González-Muñoz, N., and Gallardo, A., 2011. Effects of exotic and native tree leaf litter on soil properties of two contrasting sites in the Iberian Peninsula. *Plant and Soil*, 350, pp. 179–191. https://doi.org/10.1007/s11104-011-0893-9

Certini, G., Vestgarden, L.S., Forte, C., Tau, T. and Strand, L., 2015. Litter decomposition rate and soil organic matter quality in a patchwork heathland of southern Norway, *Soil*, 1, pp. 207–216. https://doi.org/10.5194/soil-1-207-2015

Dalal, R.C., 1998. Soil microbial biomass: What do the numbers really mean? *Australian Journal of Experimental Agriculture*, 38, pp. 649-665. https://doi.org/10.1071/EA97142

Dawoe, E.K., Isaac, M.E. and Quashie-Sam, J., 2010. Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. *Plant and Soil*, 330, pp. 55–64.https://doi.org/10.1007/s11104-009-0191-5

Domínguez, A., Bedano, C.J., Becker, A.R., and Arolfo, RV., 2014. Organic farming fosters agro-ecosystem functioning in Argentinian temperate soils: evidence from litter decomposition and soil fauna. *Applied Soil and Ecology*, 83, pp. 170–176. http://dx.doi.org/10.1016/j.apsoil.2013.11.008

Duan, H., Wang, L., Zhang, Y, Fu, X, Tsang, Y and Wu, J., 2018. Variable decomposition of two plant litters and their effects on the carbon sequestration ability of wetland soil in the Yangtze River estuary. *Geoderma*, 319, pp. 230–238. http://doi.org/10.1016/j.geoderma.2017.10.050

Fontes, A.G., Gama-Rodrigues, A.C., Gama-Rodrigues, E.F., Sales, M.V.S., Costa, M.G., and Machado, R.C.R., 2014. Nutrient stocks in litterfall and litter in cocoa agroforests in Brazil. *Plant and Soil*, 383, pp. 313–335. https://doi.org/10.1007/s11104-014-2175-9

Fox, J. and Weisberg, S., 2011. An R Companion to Applied Regression. Sage, Thousand Oaks, CA, second edition.

Hayashi, S.N., Vieira, I.C.G., Carvalho, C.J.R. and Davidson, E., 2012. Linking nitrogen and phosphorus dynamics in litter production and decomposition during secondary forest succession in the eastern Amazon. Boletim do Museu Paraense Emílio Goeldi. *Ciências Naturais*, 7, pp.283–295. https://doi.org/10.46357/bcnaturais.v7i3.591

Hothorn, T., Bretz, F. and Westfall, P., 2008. Simultaneous inference in general parametric models. *Biometrical Journal:*

Journal of Mathematical Methods in Biosciences, 50(3), pp. 346-363. https://doi.org/10.1002/bimj.200810425.

Hunt, H.W. 1977. A simulation model for decomposition in grasslands. *Ecology*, 58, pp. 469-484. https://doi.org/10.2307/1938998

Institute for Agricultural Research Metrological station, IARMS., 2021. Metrological data from IAR metrological station, Ahmadu Bello University, Samaru, Zaria Nigeria.

Kaba, J.S., 2017. Nitrogen nutrition of cocoa (*Theobroma cacao* L.) in intercropping systems with gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.). PhD Thesis of The Free University of Bozen-Bolzano, Faculty of Science and Technology, Bolzano, Italy.

Karberg, N.J., Scott, N.A. and Giardina, C.P., 2008. Methods for Estimating Litter Decomposition Chapter 8. In: C.M. Hoover, ed. *Field measurements for forest carbon monitoring: A landscape-scale approach*. New York, NY: Springer Science + Business Media: pp. 103-111.

Kumar, B.M., 2008. Litter dynamics in plantation and agroforestry systems of the tropics—a review of observations and methods. In: D.R. Batish, R.K. Kohli, S. Jose and H.P. Singh, eds. *Ecological basis of agroforestry*, Boca Raton:CRC Press.

Liao, C., Long, C. and Zhang, Q., 2022. Stronger effect of litter quality than micro-organisms on leaf and root litter C and N loss at different decomposition stages following a subtropical land use change. *Functional Ecology*, 1, pp. 1–12. https://doi.org/10.1111/1365-2435.13999

Lin, H., Li, Y., Bruelheide, H., Zhang, S., Ren, H. and Zhang, N., 2021. What drives leaf litter decomposition and the decomposer community in subtropical forests – the richness of the above-ground tree community or that of the leaf litter? *Soil Biological and Biochemistry*, 160, pp. 108314. https://doi.org/10.1016/j.soilbio.2021.108314

Lin, D., Pang, M., Fanin, N., Wang, H., Qian, S., Zhao, L., Yang, Y., Mi, X. and Ma, K., 2019. Fungi participate in driving home-field advantage of litter decomposition in a subtropical forest. *Plant and Soil*, 434, pp. 467–480. https://doi.org/10.1007/s11104-018-3840-7

Liu, P., Huang, J., Sun, O.J. and Han, X., 2010. Litter decomposition and nutrient release as affected by soil nitrogen availability and litter quality in a semiarid grassland ecosystem. *Oecologia*, 162, pp. 771-780. https://doi.org/10.1007/s00442-009-1513-7

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G. and Gattinger, A., 2017. Organic farming enhances soil microbial abundance and activity meta-analysis and meta-regression. *PLoS One*, 12(7), pp. 18-44. https://doi.org/10.1371/journal.pone.0180442

Mahmood, V., Siddique, M. R. H. and Abdullah, S. M. R., 2014. Nutrient dynamics associated with leaching and microbial decomposition of four abundant mangrove species leaf litter of the Sundarbans, Bangladesh. *Wetlands*; 34 (3), pp. 439-448. https://doi.org/10.1007/s13157-013-05

Mohammed, K. O., 2013. Mineralization of neem seed cake and effect on growth and nutrition of sorghum in a northern Guinea Savanna Alfisol. Unpublished Ph.D Thesis, Department of Soil Science, Ahmadu Bello University, Zaria. Pp. 32-35

Mohammed, A.M., Robinson, J.S., Midmore, D.J. and Verhoef, A., 2019. Leaf litter decomposition and mitigation of CO_2 emissions in cocoa ecosystems. In: A.M. Mohammed, J.S. Robinson, D.J.. Midmore and A. Verhoef. Eds.*CO_2 Sequestration*, Londo:IntechOpen. pp.20-23. https://doi.org/10.5772/intechopen.86520

Moyer, R.A., Hummer, K.E., Finn, C.E., Frei, B. and Wrolstad, R.E., 2002. Anthocyanins, phenolics, and antioxidant capacity in diverse small fruits: *Vaccinium*, *Rubus*, and *Ribes*. *Journal of Agriculture and Food Chemistry*, 50 (3), pp. 519–525. https://doi.org/10.1021/jf010625a

Naik, S.K., Maurya, S., Mukherjee, D., Singh, A.K. and Bhatt, B.P., 2018. Rates of decomposition and nutrient mineralization of leaf litter from different orchards under hot and dry sub-humid climate. *Archive of Agronomy and Soil Science* 64, pp. 560-573. http://doi.org/10.1080/03650340.2017.1362104

Novara, A., Rühl, J., La Mantia, T., Gristina, L., La Bella, S. and Tuttolomondo, T., 2015. Litter contribution to soil organic carbon in the processes of agriculture abandon. *Solid Earth,* 6, pp. 425–432. https://doi.org/10.5194/se-6-425-2015.

Okalebo, J.R., Gathua, K.W. and Woomer, P.L., 2002. *Laboratory methods of soil analysis: A working manual,* 2nd ed. Nairobi:TSBR-CIAT and SACRED Africa.

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, 44, pp. 322-331. https://doi.org/10.2307/1932179

Podong, C., Poolsiri, R., Katzensteinern K., Pengthamkeerati, P. and Thongdeenok, P., 2013 Species diversity and litter dynamics in secondary mixed deciduous forest, ThungSalaeng Lung National Park, Northern, Thailand. *Folia Forestalia Polonica*; 55, pp. 196–204. https://doi.org/10.2478/ffp-2013-0022

Quer, E., Pereira, S., Michael, T., Santonja, M., Gauquelin, T., Simioni, G., Oureival, J.M., Joffre, R., Limousin, J.M. and Aupic-Samain, A., 2022. Amplified Drought Alters Leaf Litter Metabolome, Slows Down Litter Decomposition, and Modifies Home Field (Dis) Advantage in Three Mediterranean Forests. Plants; 11, pp. 25-28. https://doi.org/10.3390/plants11192582

R Core Team., 2018. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ren, Z., Zhao, H., Fu, Y., Xiao, L., and Dong, Y., 2022. Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city, China. *Journal of Forestry Research*, *33*(3), pp. 911-922. https://doi.org/10.1007/s11676-021-01502-17

Ruwanza, S., Gaertner, M., Esler, K. J. and Richardson, D.M., 2014. Allelopathic effects of invasive *Eucalyptus camaldulensis* on germination and early growth of four native species in the Western Cape, South Africa. *Southern Forests: Journal of Forest Science*, 77, pp. 91–105. https://doi.org/10.2989/20702620.2014.965985

Saez-Plaza, Michalowski, T., Navas, M.J. and Asuero, A. G., 2013. An overview of the Kjeldahl method of nitrogen determination part 1. Early history, chemistry of the procedure, and titrimetric finish. *Critical Review in Analytical Chemistry,* 4, pp. 43-45. https://doi.org/10.1080/10408347.2013.786239

Singh, K., Trivedi, P., Singh, G., Singh, B. and Patra, D. D., 2014. Effect of different leaf litters on carbon, nitrogen and microbial activities of sodic soils. *Land Degradation Development*, 3, pp. 207-213. https://doi.org/10.1002/ldr.2160.

Singh, K.P., Singh, P.K. and Tripathy, S.K., 1999. Litterfall, litter decomposition and nutrient release patterns in four native tree species raised on coal mine spoil at Singrauli, India. *Biology and Fertility of Soils*, 29, pp. 371-378. https://doi.org/10.1007/s003740050567

Swift, J.A., Heal, O.W. and Anderson, J.M., 1979. Decomposition in Terrestrial Ecosystems. Oxford:Blackwell Scientific Publications.

Tarfa, B.D., 2001. Effect of some selected indigenous tree foliage on soil fertility and productivity of a savanna soil. Ph. D. Thesis, Department of Soil Science, Faculty of Agriculture, Ahmadu Bello University, Samaru, Zaria; 164pp.

Taylor, B.R., Parkinson, D. and Parsons W.F.J., 1989. Nitrogen and lignin control of hardwood leaf decomposition dynamics. *Ecology*, 63, pp. 621-626. https://doi.org/10.2307/1938416

Triadiati, S., Tjitrosemito, E., Sundarsono, G., Qayim, I. and Leuschner, C., 2011. Litterfall production and leaf-litter decomposition at natural forest and cacao agroforestry in Central Sulawesi, Indonesia. *Asian Journal of Biology Science*, 4(2), pp. 21–234.

Vitousek, P.M., Turner, D.R., Parton, W.J. and Sanford R.L., 1994. Litter decomposition on the Mauna Loa environmental matrix, Hawaii: patterns, mechanisms, and models. *Ecology*, 75, pp. 418-429. https://doi.org/10.2307/1939545

Watson, C., Atkinson, D., Gosling, P., Jackson, L. and Rayns, F., 2002. Managing soil fertility in organic farming systems. *Soil Use and Management*, 18, pp. 239-247. https://doi.org/10.1111/j.1475-2743.2002.tb00265.x

Weider, R.K., Carrel, J.E., Rapp, J.K. and Kucera, C.L., 1983. Decomposition of tall fescue (*Festuca elatior* var. arundinacea) and cellulose litter on surface mines and tallgrass Prairie in central Missouri, USA. *Journal of Applied Ecology*, 12 (1), pp. 45-49. https://doi.org/10.2307/2403394.

Wei, T., and Viliam, S., 2021. R package "corrplot": visualization of a Correlation Matrix. R package version 0.92. Available at: https://github.com/taiyun/corrplot

Xiao, H., Sheng, M., Wang, L., Guo, C., and Zhang, S., 2022. Effects of short-term n addition on fine root morphological features and nutrient stoichiometric characteristics of *Zanthoxylum bungeanum* and Medicago sativa seedlings in southwest China karst area. *Journal of Soil Science and Plant Nutrition*, *22*(2), pp. 1805-1817. https://doi.org/10.1007/s42729-022-00513-5

Zhang, H., Huang, Y., An,s., Zeng, Q., Wang, B., Bai, X and Huang, Q., 2023. Decay stages and meteorological factors affect microbial community during leaf litter in situ decomposition. *Soil Ecology Letters*. 5(3), pp. 220160. https://doi.org/10.1007/s42832-022-0160-4

Zhu, J., Qiaoling, Y. and Changjie, J., 2010. Comparison of soil microbial biomass C, N, and P between natural secondary forests and *Larix olgensis* plantations under temperate climate. In: *World Congress of Soil Science, Soil Solutions for a Changing World*. Brisbane, Australia. Pp 23.