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DETERMINATION OF LEAF LITTER INPUT, QUALITY AND DECOMPOSITION RATES IN YOUNG *Nauclea diderrichii* AND *Terminalia superba* PLANTATIONS IN NIGERIA

Olajuyigbe S. O.* and Adebo M. O.
Department of Forest Production and Products, Faculty of Renewable Natural Resources, University of Ibadan, Ibadan, Nigeria
***Corresponding author:** *so.olajuyigbe@mail1.ui.edu.ng, lekito2010@gmail.com;* +2348079279357

ABSTRACT

Using litter traps and a litterbag experiment, the input, decomposition rates and changes in chemical characteristics of leaf litter were evaluated in seven-year-old Nauclea diderrichii and Terminalia superba plantations in Nigeria. Four plots (25 m by 25 m) were laid in the Nauclea diderrichii plantation, while three (25 m by 25 m) were laid in the Terminalia superba plantation. One litter trap was placed in each plot, while 30 litterbags containing leaf litter of each species were randomly placed in each plantation for 80 days. Litter input per month, leaf litter weight loss, nitrogen, organic carbon, phosphorus, lignin, polyphenol contents, C:N and lignin: N ratios of the litter samples were determined. After four months, there was no significant difference in the monthly litter input to each plantation. However, monthly litter input was higher in Nauclea stand (549.21kg ha^{-1}) than Terminalia (109.02 kg ha^{-1}). After 80 days, 39.81% and 54.15% of leaf litter weight was remaining for Terminalia superba and Nauclea diderrichii, respectively. The single exponential decay constants were 0.0093 day^{-1} (Nauclea diderrichii) and 0.0096 day^{-1} (Terminalia superba). As decomposition progressed, nitrogen, phosphorus, organic carbon, lignin and polyphenols varied differently for the two species. Phosphorus and C: N ratio increased with time of decomposition for both species. However, the C: N ratio of Terminalia leaf litter had a sudden decrease after 80 days, suggesting mineralization of the leaf litter.

Keywords: decay constant; substrate quality; native species monocultures; litterbag experiment; decay curve

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INTRODUCTION

Litter production and nutrient cycling in plantations play important roles in nutrient turnover, maintenance of soil fertility and site productivity. The litter pool is a major pathway for the return of organic matter and nutrients from plant vegetative parts to the soil (Odiwe and Moughalu 2003; Dent *et al.*, 2006; Sari *et al.*, 2022). The pool contributes significantly to the humus layer formation of forest soils; and releases nutrients during microbial decomposition of organic materials (Triadiati *et al.*, 2011; Rojas *et al.*, 2017). Hence, it is estimated that leaf litter accounts for 80% of the total litter produced annually and supplies 70% of the annual nitrogen input to soils (Bauer *et al.*, 2000; Berhnard-Reversat and Loumeto, 2002).

The decomposition of litter is an essential process, which influences detrital turnover, nutrient release and cycling in tropical plantations (Rojas *et al.*, 2017). High quality leaf litter can be described as organic material with a high decay rate and this signifies the absence of decay inhibitory substances, high energy and nutrient supply for microbial use, high nitrogen and phosphorus concentration, and a high proportion of easily degradable carbon-based compounds (Moore *et al.*, 2006; Liu *et al.*, 2020). Nevertheless, decomposition rates and nutrient release patterns vary among leaf litter of different tree species, depending on the litter quality, environmental conditions, and the nature and abundance of decomposing organisms present on site (Bradford *et al*., 2016; Wang *et al*., 2008; Sari *et al*., 2022). In addition, the leaf litter input which varies from deciduous to evergreen plantations, influence the rate of decomposition, turnover and microbial activity. Consequently, the quantities of soluble C, N, lignin and polyphenol concentrations are common physicochemical criteria that help define detrital substrate quality. Previous studies have used C: N and C: lignin ratios to predict stages of decomposition and nutrient release from forest litter (Olajuyigbe *et al.*, 2012; Negash and Starr, 2021; Sari *et al*., 2022).

In the tropics, most studies on leaf litter accumulation and decomposition have focused on natural forests, secondary forests and monocultures of exotic species (Odiwe and Moughalu, 2003; Oladoye *et al*., 2008; Moughalu and Odiwe, 2011; Oziegbe *et al*., 2011). However, there is limited information on the leaf litter accumulation, nutrient turnover and decomposition dynamics of indigenous tree species monocultures. The information obtained on the chemical changes that occur in leaf litter as they decompose on the forest floor; will be useful in the determination of fertility and productive ability of such plantations, as well as in the selection of suitable silvicultural management methods that would increase productivity.

The establishment of monocultures of hardwood species has been suggested as a viable means of increasing timber supply and reducing the exploitation of natural forests in the tropics. Two of such species of high economic importance are *Nauclea diderrichii and Terminalia superba* (Varmola and Carle, 2002; Adjonou *et al*., 2014). *Nauclea diderrichii* is a member of the Rubiaceae family, while *Terminalia superba* is from the Combretaceae family. They are highly valued timber species, naturally occurring in subtropical or tropical moist lowland forests, but are threatened by habitat loss and overexploitation. Hence, this study determined the litter input, decomposition rates and changes in chemical characteristics of leaf litter in *Nauclea diderrichii* and *Terminalia superba* monocultures.

MATERIALS AND METHODS

Study area

The study was conducted in *Nauclea diderrichii* and *Terminalia superba* plantations located in the Forestry Research Institute of Nigeria, Ibadan, Nigeria. The site lies on latitude 7º23´15´´ to 7º24´15´´N and longitude 3º51´00´´ to 3º52´15´´E. The region experiences bimodal rainfall patterns with peaks in June and July, as well as in September and October. The mean annual rainfall is 1,208 mm with mean minimum and maximum temperatures of 18.07 ˚C and 34.4 ˚C, respectively (Ariwaodo *et al.*, 2012; Ojo, 2017). The two plantations were established in 2011, using the taungya system. The *Nauclea diderrichii* stand was established using a 4 m by 4 m spacing on a 6 ha plantation, while the *Terminalia superba* stand was established using a 2 m by 2 m spacing on a 2 ha plantation.

Leaf litter collection

In this study, four plots (25 m x 25 m each) were established in the *Nauclea diderrichii* plantation, while three were laid in the *Terminalia superba* plantation. One litter trap (1.5 m x 1.5 m) was erected at the centre of each of the sample plots and used to collect leaf litter (Figure 1), falling from the tree canopies, from March to June 2017. Each litter trap consisted of 1 mm mesh nylon netting (on a wooden frame) suspended from a wire hoop and raised 50 cm above the ground. The litter traps were emptied at the end of each month. The litter collected was oven dried at 60ºC to constant dry weight. Then, monthly litter input per hectare was estimated using equation 1:

$$Litter\ input\ (kg\ ha^{-1}\ month^{-1} = \frac{total\ litterfall\ (kg)}{area\ of\ litter\ trap\ (m^2)}\ x\ 10{,}000\ (m^2) \quad ….. (1)$$

Figure 1. Littertrap erected at the centre of a sample plot in the *Terminalia superba* plantation

Litterbag decomposition experiment

The litterbag technique was used to determine leaf litter decomposition rates for the two species. Following the methods of Wang *et al*. (2008), fresh leaf litter were collected from the lower branches of standing trees in each plantation. The leaf litter were oven dried at 60 ˚C until a constant weight was attained, after which 20 g and 15 g of *Nauclea diderrichii and Terminalia superba* leaf litter were weighed into litterbags (1 mm mesh size). The dimensions of the litterbags were 50 cm by 40 cm for *Nauclea diderrichii*, and 30 cm by 30 cm for *Terminalia superba.* Thirty litterbags containing leaf litter of each species were randomly distributed on the soil in each plantation and pinned down with pegs to prevent their displacement and ensure contact with the soil (Figure 2). Six litterbags were randomly retrieved from each plantation after 0, 20, 40, 60, and 80 days. The materials recovered from the litterbags were air-dried and carefully cleaned to remove attached debris such as soil particles and fine roots. Then, the leaf litter samples were oven-dried at 60 °C to constant weight.

The initial weight remaining (WR) for leaf litter at each retrieval point was determined, using equation 2:

$$WR\ (\%) = \frac{x_1}{x_0}\ x\ 100\ \ldots.\ (2)$$

Where:
WR (%) is the percentage of leaf litter weight remaining
x_1 is the weight of leaf litter (g) at the time of retrieval
x_o is the initial weight of leaf litter (g)

The decay constant (k) of the leaf litter of each tree species was estimated using a single exponential decomposition model as shown in equation 3:

$$x_t = x_o e^{-kt} \ldots\ldots (3)$$

Where:
x_t is the remaining weight of leaf litter (g) after a given period of time t, x_o is the initial weight (g) of leaf litter, k is the decay constant, t is the time (days).

The half-life (t_{50}), which is the time required for 50% of leaf litter to decompose, was calculated using equation 4:

$$t_{50} = \frac{0.693}{k} \ldots\ldots (4)$$

Figure 2. Litterbags randomly placed on the soil in the *Nauclea diderrichii* plantation

Determination of leaf litter quality

Sub-samples obtained from the oven-dried leaf litter were milled and sieved through a 0.5 mm mesh. The chemical composition of the leaf litter before and after decomposition were determined. The carbon content in the leaf litter was measured using Walkley – Black Wet Oxidation Method. Hence, milled leaf litter (0.1 g) was digested in 10 ml $K_2Cr_2O_7$ solution, before 20 ml of concentrated H_2SO_4 was added, rapidly. The solution was allowed to stay for 10 minutes after which 100 ml of distilled water was added and allowed to cool. The cooled solution was titrated with 0.5 N Ferrous Ammonium Sulphate solution. Percentage organic carbon was then calculated using titer value (TV) in equation 5.

$$\text{\% Organic Carbon} = \frac{\text{T.V} \times 0.5 \times 0.003 \times 1.33}{0.1g} \times 100 \text{ ….. (5)}$$

Total nitrogen content in leaf litter was determined following the Micro-Kjeldahl digestion procedure described by Wang *et al.* (2008). Sub samples (0.5g) were digested in 10 ml of concentrated H_2SO_4, using a catalyst mixture ($CuSO_4$, K_2SO_4 and selenium powder) and distillation. Lignin content of the leaf litter was estimated using the Klason method of lignin content determination. Thus, 2 g of the leaf litter subsample was digested in a 250 ml beaker with 15 ml of 72% concentrated H_2SO_4 for 2 hours at room temperature. After digestion, 475 cm^3 of water was added and the content allowed to boil for 4 hours on a heating mantle. The boiled sample was then allowed to settle overnight, filtered and washed with hot distilled water to remove the acid until it was neutral on litmus paper. The filtered paper was oven dried at 85° C to a constant weight. The weight of the oven dried sample was measured and the lignin content expressed as a percentage of the original sample (Eqn. 6).

$$\text{Lignin content (\%)} = \frac{Weight\ of\ lignin}{Weight\ of\ initial\ sample} \times 100\% \text{ ….(6)}$$

Total phenolic content of leaf litter was determined using Folin-Ciocalteau method as described by Chan *et al.* (2006) and Li *et al.*, (2016). Milled leaf litter (50 mg) was introduced into 15 ml of 70% acetone (acetone-water, 70:30, v/v) and the active ingredients extracted using an ultrasonic wave extractor, and then centrifuged at 4°C and 5000 r/min for 10 minutes. Then, 1.5 ml of Folin-Ciocalteau reagent (diluted 10 times with distilled water) and 1.2 ml of sodium carbonate solution (Na_2CO_3) (7.5w/v) was added and solution mixed thoroughly. The solution was allowed to react in darkness for 40 minutes, and the absorbance was measured at 725 nm.

Data Analysis

Data were analysed using descriptive and inferential statistics (one - way analysis of variance). The single exponential decay model was used to determine the decay constant for leaf litter of *Nauclea diderrichii* and *Terminalia superba.* The Holm-Sidak multiple comparison test ($p<0.05$) was used to separate significantly different means. Statistical analysis was performed using Sigma Stat 11 software.

RESULTS

Over the four-month period, there was no significant difference in the monthly litter input to the *Nauclea diderrichii* ($p = 0.085$) and *Terminalia superba* ($p = 0.066$) plantations. However, monthly litter input increased from March to June 2017 in the *Nauclea diderrichii* plantation (Figure 3). On the contrary, there was a decrease in the litter input in May in the *Terminalia superba* plantation. (Figure 4). Mean litter input per month was 549.21 kg ha^{-1} and 109.02 kg ha^{-1} in the *Nauclea* and *Terminalia* stands, respectively.

The weight remaining differed significantly for leaf litter of *Nauclea diderrichii* ($p = 0.007$*) and Terminalia superba* ($p <0.001$). However, the post hoc analysis revealed that higher weight loss was recorded for *Nauclea* at 80 days, while weight loss for *Terminalia* leaf litter at 60 and 80 days differed from others. The weight loss of leaf litter bags increased with time for *Nauclea diderrichii* and *Terminalia superba* (Table 1). After 80 days, 54.14% and 39.81% of the initial weight was remaining for *Terminalia superba* and *Nauclea diderrichii*, respectively. The k constant (0.0093 day^{-1}) for *Nauclea diderrichii* leaf litter was similar to that of *Terminalia superba* (0.0096 day^{-1}). Leaf litter weight loss followed the single exponential decay curve pattern for both species. However, R^2 values for both species suggest that there were other factors influencing leaf litter decomposition besides time of decay and weight loss (Figure 5 and 6). The t_{50} values indicated that 50% of the leaf litter initial weight would be lost after 74.5 and 72.2 days, respectively.

The proportion of chemical constituents followed a similar trend in both species with organic carbon > lignin > polyphenols > phosphorus > nitrogen. However, as decomposition progressed, nitrogen, phosphorus, carbon, lignin and polyphenols followed different pathways of nutrient release. Nitrogen content significantly differed for *Nauclea diderrichii* ($p<0.001$), but did not differ among *Terminalia superba* leaf litter ($p = 0.357$), over the time of decay. The phosphorus content significantly increased with time of decay for *Nauclea diderrichii* ($p<0.001$) and *Terminalia superba* ($p<0.001$) leaf litter. Organic carbon significantly differed among the leaf litter over the time of decay. For *Nauclea diderrichii* leaf litter ($p<0.001$), organic carbon slightly decreased (from 39.1% to 35.3%) after 20 days, and then continued to increase afterwards (53.3% at 80 days). However, nitrogen, lignin and polyphenol contents gradually decreased with leaf litter decomposition for both *Nauclea diderrichii* and *Terminalia superba*. The C: N ratio was higher than Lignin: N ratio before and during decomposition for both species. However, a drop was observed for the C: N ratio of *Terminalia superba* leaf litter after 80 days (25.05).

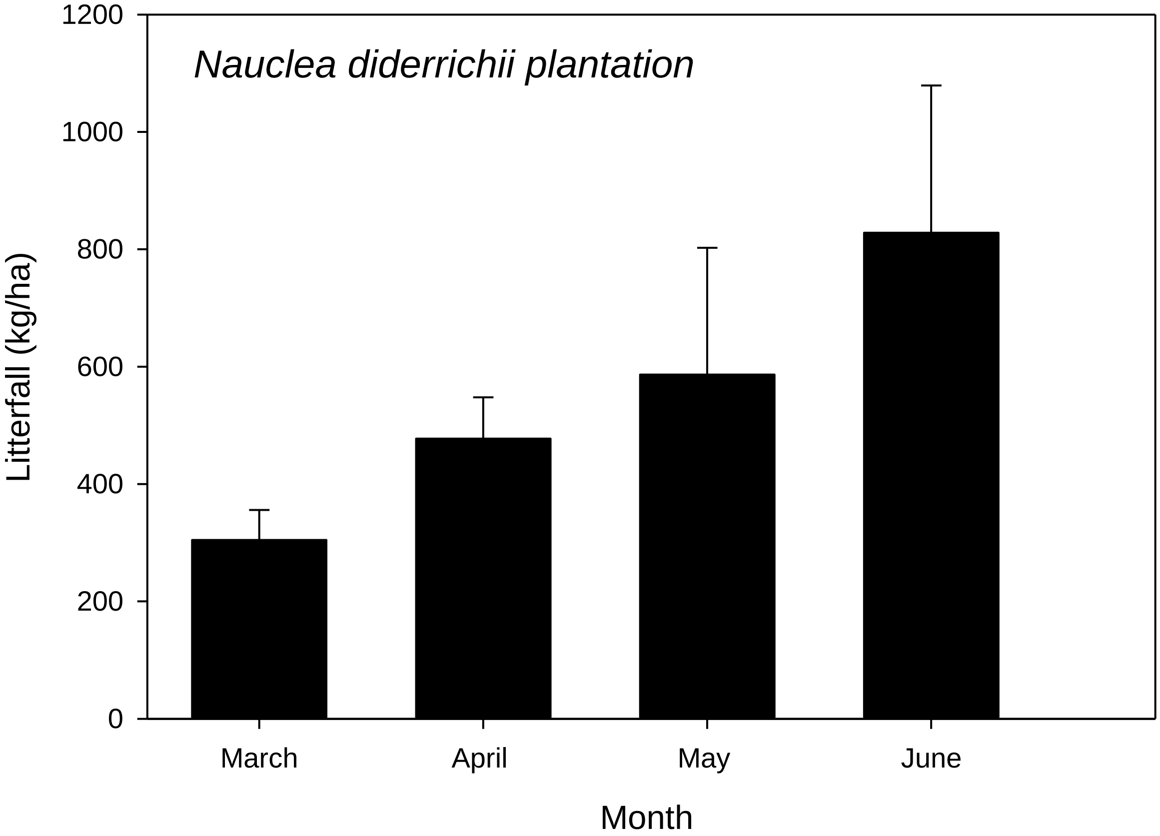

Figure 3. Leaf litter input in the seven-year old *Nauclea diderrichii* plantation from March to June 2017 (mean ± S.E.)

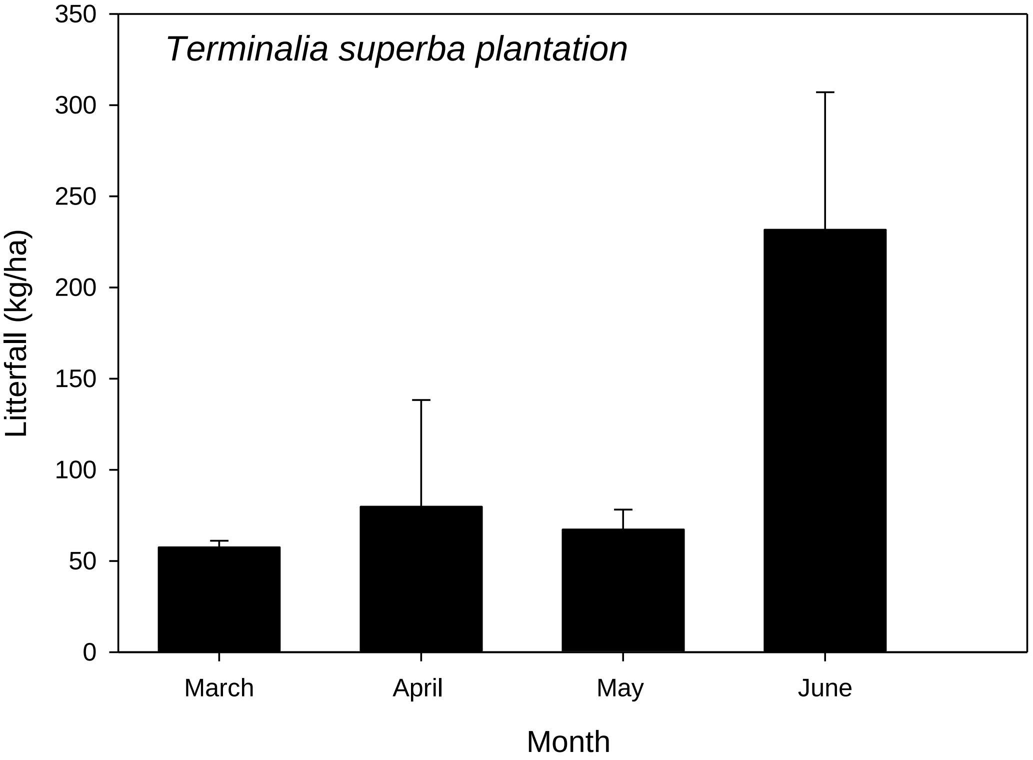

Figure 4. Leaf litter input in the seven-year old *Terminalia superba* plantation from March to June 2017 (mean ± S.E.)

Table 1. Change in weight and chemical characteristics of leaf litter of *Nauclea diderrichii* and *Terminalia superba*, decomposing in litterbags for 80 days

Days	Initial weight remaining (%)	Nitrogen (%)	Phosphorus (mg/100g)	Organic Carbon (%)	Polyphenols (%)	Lignin (%)	C: N ratio	Lignin: N ratio
				Nauclea diderrichii				
0	100^{a}	1.13^{a}	6.90^{a}	39.1^{ab}	8.79	28.18^{a}	34.6	24.94
20	88.91^{a}	1.12^{a}	7.87^{b}	35.3^{a}	8.50	19.18^{b}	31.52	17.13
40	74.63^{a}	0.98^{b}	8.16^{c}	36.5^{a}	8.10	18.90^{b}	37.24	19.29
60	70.95^{a}	0.93^{b}	8.57^{d}	46.6^{bc}	7.91	16.38^{b}	50.11	17.61
80	54.15^{b}	0.91^{b}	8.94^{e}	53.3^{c}	6.76	14.89^{b}	58.57	16.36
				Terminalia superba				
0	100^{a}	0.98	7.28^{a}	34.51^{a}	9.19	22.87^{a}	35.21	23.34
20	87.68^{a}	0.96	7.67^{b}	32.25^{a}	8.24	18.67^{b}	33.59	19.45
40	79.34^{a}	0.95	7.89^{c}	35.71^{a}	8.47	15.27^{bc}	37.59	16.07
60	60.50^{b}	0.90	8.19^{d}	39.57^{b}	8.93	12.29^{c}	43.97	13.66
80	39.81^{b}	0.87	8.34^{d}	21.79^{c}	6.76	14.52^{c}	25.05	16.69

Mean values in columns with same letters (in superscript) were not significantly different at p<0.05

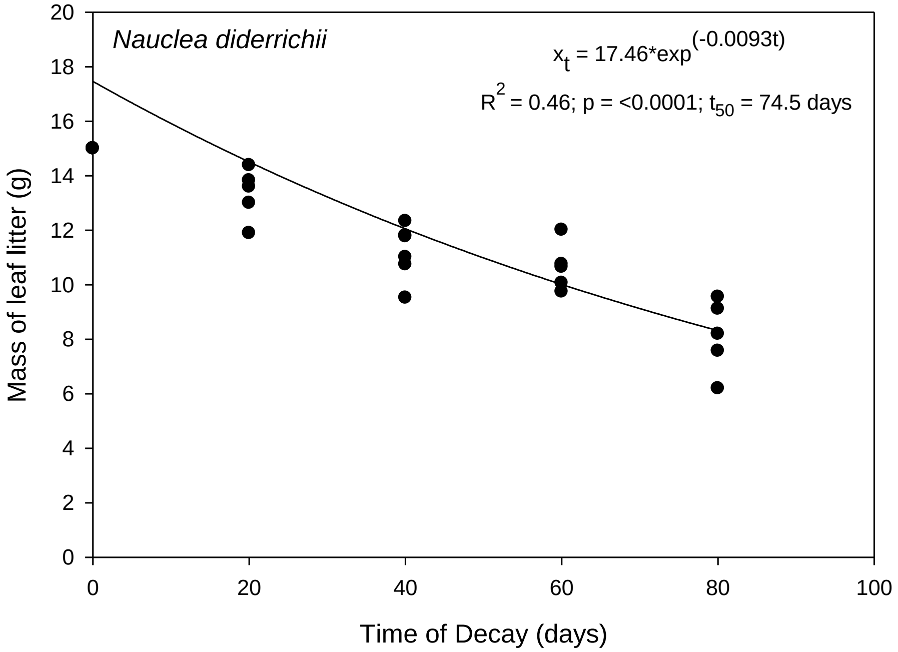

Figure 5: Single exponential decay curve for leaf litter of *Nauclea diderrichii,* after 80 days of decomposition in litterbags

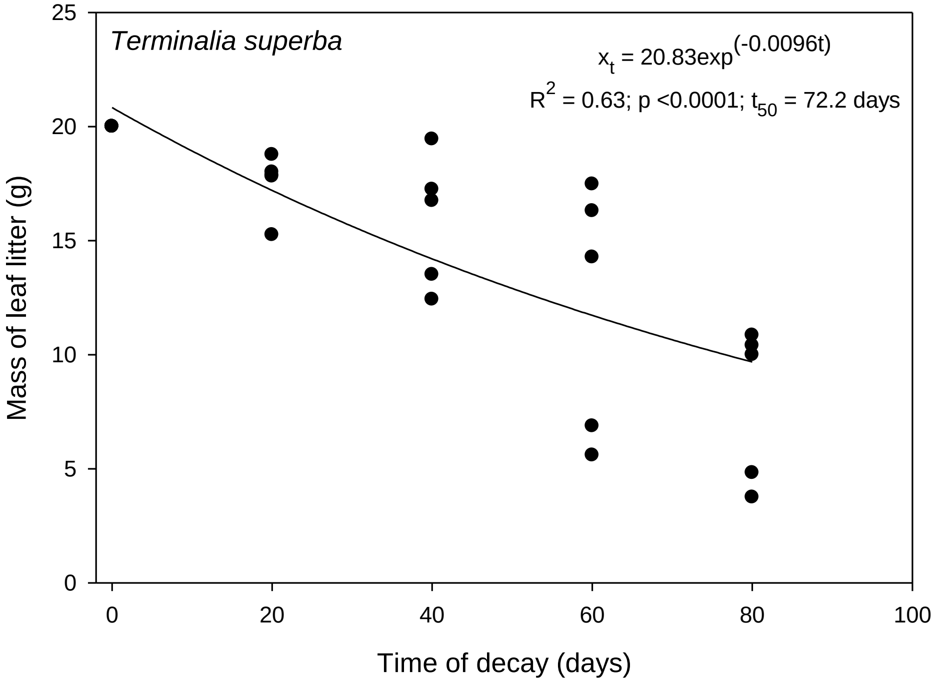

Figure 6: Single exponential decay curve for leaf litter of *Terminalia superba,* after 80 days of decomposition in litterbags

DISCUSSION

The high litter input is indicative of high productivity, particularly in the *Nauclea diderrichii* plantation. It is also a critical factor in the nutrient turnover and availability through litter decomposition. This corroborates the findings of Ashagrie and Zech, (2013) who reported that litter input were major drivers of productivity and nutrient cycling in both exotic plantations (*Eucalyptus globulus* and *Cupressus lusitanica*) and natural forest (dominated by *Podocarpus falcatus*) in Ethiopia. The increase in litter fall was partly in response to the increased frequency of rainfall usually observed in May and June as previously reported in tropical plantations (Oladoye *et al.*, 2008; Sari *et al*., 2022). Some other factors that influence litter fall in tropical forests include tree density, stand age, and canopy cover (Berhnard-Reversat and Loumeto, 2002). The litter input for and *Nauclea* (549.21 kg ha^{-1}) and *Terminalia* (109.02 kg ha^{-1}) stands fall within the biomass input suggested for juvenile plantations by Berhnard-Reversat and Loumeto (2002). Previous studies had shown that litter fall increased with juvenile age in *Pinus caribaea* (Kadeba 1998) and *Eucalyptus* plantations (Berhnard-Reversat *et al.*, 1999*)*. This increase in biomass input is important for *Nauclea diderrichii* and *Terminalia superba*, which have become priority species, increasingly being used in plantation establishment, due to their high potentials for supply of timber, electric poles and other forest products (Adjonou *et al*., 2014).

The quantity of chemical constituents in leaf litter determines its quality and is a contributing factor to the rate of decomposition. The high rate of decomposition observed for leaf litter of both species is a typical characteristic of tropical species (Powers *et al.*, 2009; Negash and Starr, 2021). Hence, most indigenous tree plantations have low litter accumulation, because organic matter decomposers are well adapted to the environment and are supported by a climate that favours rapid decomposition (Berhnard-Reversat and Loumeto, 2002; Liu *et al*., 2020). In addition, tree species with high nitrogen and low lignin content decompose, rapidly, with C: N ratios > 20 indicating slow rates of decomposition (Schuur *et al.*, 2001; Sun *et al.,* 2004). The k values observed for the two species were within the range of decay constants for some tropical plantation tree species (0.01 - 0.076 day^{-1}) (Kumar, 2008). The species studied were estimated to lose 50% of their initial weight in 74.5 (*Nauclea diderrichii)* and 72.2 days (*Terminalia superba*), respectively. The t_{50} values observed in this study compare well with that of some other tropical species such as *Leucaena leucocephala* (60 days) (Oladoye *et al.*, 2008), *Mangifera indica* (95–112 days), *Milletia ferruginea* (41–76 days) and *Erythrina brucei* (52–67 days) (Negash and Starr, 2021). The exponential decay model indicated that the decay constant explained 46% and 63% of the leaf litter initial weight loss suggesting that other factors such as climate and microbial communities also contribute to litter decomposition (Waring, 2012; Liu *et al*., 2020).

Nitrogen, lignin and polyphenols were increasingly released as decomposition progressed suggesting organic matter breakdown. These trends are in agreement with Li *et al.* (2016) and Negash and Starr, (2021). Polyphenols and lignin have been reported to bind strongly to organic N in litter, to protect it from microbial enzymatic attack (Isaac and Nair 2005; Wang *et al.,* 2008). Hence, organic materials of low nutrient quality i.e. high lignin and/or polyphenols release smaller proportions of total nitrogen initially while the remainder is released at a continuous slow rate (Kumar, 2008). After 80 days, nitrogen release was observed to have been higher than organic carbon as decomposition progressed. As lignin and polyphenols decreased, the nitrogen released increased in *Terminalia superba* leaf litter, while nitrogen loss followed a similar pattern with lignin and polyphenols in *Nauclea diderrichii*. The gradual release of nitrogen in this study corroborates the assertion that nitrogen is not a limiting factor to organic matter decomposition in tropical forest (Waring, 2012; Negash and Starr, 2021). Phosphorus had the lowest nutrient release from the decomposing leaf litter in both plantations. This is because net retention of phosphorus or a low rate of phosphorus loss have been associated with litter decomposition (Cleveland *et al.*, 2006; Hobbie and Vitousek, 2000).

CONCLUSIONS

In this study, litter input varied between the *Nauclea diderrichii* and *Terminalia superba* plantations and was influenced by rainfall. The leaf litter quality changed as decomposition progressed, and this influenced the release of the chemical constituents in the organic matter. However, the C: N and Lignin: N ratios did not necessarily result in an immobilization of nutrients in the leaf litter of the two species. Instead, there was a rapid break down of lignin and polyphenols, which were gradually mineralized. Phosphorus on the other hand increased in the leaf litter as decomposition progressed. The findings suggest that silvicultural management interventions that would promote increased litter input and enhanced nutrient cycling are required for young indigenous tree plantations in Nigeria.

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REFERENCES

Adjonou K, Nuto Y, Bosu PP, Adu-Bredu S, Kokutse AD, Kokou K (2014). Natural distribution of *Nauclea diderrichii* (Rubiceae) in semi deciduous forest of Togo (West Africa) and implementation of integrated silviculture. *American Journal of Plant Sciences* 5(9). doi: 10.4236/ajps.2014.59135

Ariwaodo JO, Adeniji KA, Akinyemi OD (2012). The vascular flora on assemblage stream bank, Forestry Research Institute of Nigeria (FRIN) premises, Ibadan Nigeria. *Annals of Biological Research* 3(4): 1757-1763.

Ashagrie Y, Zech, W (2013). Litter production and nutrient cycling in two plantations and a *Podocarpus falcatus* dominated natural forest ecosystems in south-eastern highlands of Ethiopia. African *Journal of Agricultural Research* 8(38): 4810-4818.

Bauer GA, Persson H, Persson T (2000). Linking plant nutrition and ecosystem processes in carbon and nitrogen cycling in European forest ecosystem. In: Schulze (ed). Carbon and nitrogen cycling in European Forest Ecosystems. Ecological Studies, vol. 142. Springer, Berlin, Heidelberg. pp 63-95. https://doi.org/10.1007/978-3-642-57219-7_4

Berhnard-Reversat F, Laclau JP, Loubana PM, Loumeto JJ, Mboukou-Kimbatsa IMC, Reversat G (1999). Changes in biological factors of fertility in managed Eucalyptus plantations grown on a savanna soil in Congo. The International Workshop on the Rehabilitation of Degraded Tropical Forestry Ecosystems, 24 November, 1999, CIFOR in Bogor, Indonesia.

Berhnard-Reversat F, Loumeto J (2002). The litter system in African forest-tree plantations. In: Vikram RM (ed.). Management of tropical plantation-forests and their soil-litter system (No. SD390. 3. T76 M36).

Bradford MA, Berg B, Maynard DS, Wieder WR, Wood SA (2016). Future directions: understanding the dominant controls on litter decomposition. *Journal of Ecology*. https://www.jstor.org/stable/24762886

Chan EWC, Linn YY, Chew YL (2006). Antioxidant activity of *Camellia sinensis* leaves and tea from a lowland plantation in Malaysia. *Food Chemistry* 102:1214-1222. https://doi.org/10.1016/j.foodchem.2006.07.009

Cleveland CC, Reed SC, Townsend AR (2006). Nutrient regulation of organic matter decomposition in a tropical rain forest. *Ecology* 87(2): 492-503. https://www.jstor.org/stable/20068962

Dent DH, Bagchi R, Robinson D, Majalap-Lee N., Burslem DFRP (2006). Nutrient fluxes via litterfall and leaf litter decomposition vary across a gradient of soil nutrient supply in a lowland tropical rain forest. *Plant and Soil* 288:197–215. https://doi.org/10.1007/s11104-006-9108-1

Hobbie SE, Vitousek PM (2000). Nutrient limitation of decomposition in Hawaiian forests. *Ecology* 81(7): 1867-1877.

Isaac SR, Nair MA (2005). Biodegradation of leaf litter in the warm humid tropics of Kerala, India. *Soil Biology and Biochemistry* 37:1656–1664. https://doi.org/10.1016/j.soilbio.2005.02.002

Kadeba O (1998). Above ground nutrient dynamics of Caribbean pine (*Pinus caribaea*) plantation ecosystems. In: Schulte, A, Kadeba O (eds), Soil tropical forest ecosystems: characteristics, ecology and management. pp 125-132.

Kumar BM (2008). Litter dynamics in plantation and agroforestry systems of the tropics: a review of observations and methods. In: Batish DR, Kohli R K, Jose S, Singh HP (eds). Ecological Basis of Agroforestry, CRC Press. pp 181-216.

Li H, Xu L, Wu F, Yang W, Ni X, He J (2016). Forest gaps alter the total phenol dynamics in decomposing litter in an Alpine Fir Forest. *PLoS One* 11(2):e0148426. https://doi.org/10.1371/journal.pone.0148426

Liu J, Liu X, Song Q, Compson ZG, LeRoy CJ, Luan F, Wang H, Hu Y, Yang Q (2020). Synergistic effects: a common theme in mixed-species litter decomposition. *New Phytologist* 227(3):757-765.

Moore TR, Trofymow JA, Prescott CE, Fyles J, Titus BD (2006). Patterns of carbon, nitrogen and phosphorus dynamics in decomposing foliar litter in Canadian forests. *Ecosystems* 9:46–62. https://doi.org/10.1007/s10021-004-0026-x

Negash M, Starr M (2021). Litter decomposition of six tree species on indigenous agroforestry farms in south-eastern Ethiopia in relation to litterfall carbon inputs and modelled soil respiration. *Agroforestry Systems* 95(4): 755-766. https://doi.org/10.1007/s10457-021-00630-w

Odiwe AI, Moughalu JI (2003). Litter fall dynamics and forest floor litter as influenced by fire in a secondary lowland rain forest in Nigeria. *Tropical Ecology* 44(2):241-249.

Ojo MO (2017). Effect of provenance and soil type on the growth of *Tectona grandis* Linn. *Continental Journal of Agricultural Science* 11(2):26–34. https://doi.org/10.5281/zenodo.831481

Oladoye O, Ola-Adams BA, Adedire MO, Agboola DA (2008). Nutrient dynamics and litter decomposition in *Leucaena leucocephala* (Lam.) De Wit plantation in the Nigerian derived savanna. West African *Journal of Applied Ecology* 13.

Olajuyigbe S, Tobin B, Hawkins M, Nieuwenhuis M (2012). The measurement of woody root decomposition using two methodologies in a Sitka spruce forest ecosystem. *Plant and Soil* 360:77–91.

https://doi.org/10.1007/s11104-012-1222-7

Oziegbe MB, Muoghalu JI, Oke SO (2011). Litterfall, precipitation and nutrient fluxes in a secondary lowland rain forest in Ile-Ife, Nigeria. *Acta Botanica Brasilica* 25(3): 664-671.

Powers JS, Montgomery RA, Adair EC, Brearley FQ, DeWalt SJ, Castanho CT, … González-Iturbe, JA (2009). Decomposition in tropical forests: a pan-tropical study of the effects of litter type, litter placement and mesofaunal exclusion across a precipitation gradient. *Journal of Ecology* 97(4):801-811.

Rojas MJ, Caicedo V, Jaimes Y (2017). Biomass decomposition dynamics in agroforestry systems with *Theobroma cacao* L. in Rionegro, Santander (Colombia). *Agronomía Colombiana* 35(2):182-189. https://doi.org/10.15446/agron.colomb.v35n2.60981

Sari RR, Rozendaal D, Saputra DD, Hairiah K, Roshetko JM, van Noordwijk M (2022). Balancing litterfall and decomposition in cacao agroforestry systems. *Plant and Soil* 473:251–271. https://doi.org/10.1007/s11104-021-05279-z

Schuur EAG, Chadwick OA, Matson PA (2001). Carbon cycling and soil carbon storage in mesic to wet Hawaiian montane forests. *Ecology* 82:3182–96.

Sun OJ, Campbell J, Law BE (2004). Dynamics of carbon stocks in soils and detritus across chronosequences of different forest types in the Pacific Northwest, USA. *Global Change Biology* 10:1470–81.

Triadiati S, Tjitrosemito GE, Sudarsono, Qayim I, Leuschner C (2011). Litter production and leaf-litter decomposition at natural forest and cacao agroforestry in Central Sulawesi, Indonesia. *Asian Journal of Biological Sciences* 4: 221-234.

Varmola MI, Carle JB (2002). The importance of hardwood plantations in the tropics and sub-tropics. *International Forestry Review* 4 (2): 110-121.

Wang Q, Wang S, Huang Y (2008). Comparisons of litterfall, litter decomposition and nutrient return in monoculture *Cunninghamia lanceolata* and a mixed stand in Southern China. *Forest Ecology and Management* 255:1210-1218. https://doi.org/10.1016/j.foreco.2007.10.026

Waring BG (2012). A meta-analysis of climatic and chemical controls on leaf litter decay rates in tropical forests. *Ecosystems* 15(6): 999 - 1009. https://doi.org/10.1007/s10021-012-9561-z