Research Article

Decomposition and nutrient release from the mixed leaf litter of three agroforestry species in the Sudanian zone of West Africa

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Abstract
This study was carried out to determine the rates of decomposition and nutrient release from pure and mixed leaf litter samples of three agroforestry species (*Azolla africana* Desv., *Detarium microcarpum* Guill. and Perr. and *Vitellaria paradoxa* C.F.Gaertn.) that have potential use as green manure. Litterbags containing a total of 5 g of pure and mixed leaf litter of different quality levels were incubated under field conditions from July to November in 2017. Litter decomposition and nutrient release (N, P, and K) rates were assessed in each litterbag. The decomposition rate (k) indicated that pure *A. africana* litter decomposed faster ($k = 0.406$ week^{-1}) than its mixture with *V. paradoxa* ($k = 0.114$ week^{-1}) and *D. microcarpum* ($k = 0.103$ week^{-1}). The slowest decomposition rates were found for the pure *D. microcarpum* ($k = 0.075$ week^{-1}) and *V. paradoxa* ($k = 0.071$ week^{-1}) leaf litters. Mixing with *A. africana* litter increased the decomposition rate of both *D. microcarpum* and *V. paradoxa* leaf litter. We conclude that mixing litter of different quality can accelerate the decomposition of pure litter with poor quality and represents a practical biomass management option for farmers to improve nutrient cycling in agroforestry systems.

Keywords *Azolla africana* · Litter quality · Non-additive effect · Interaction dynamic · Soil fertility

1 Introduction

In sub-Saharan Africa, soil degradation and fertility loss are the most serious threats to food security and poverty alleviation [1]. In particular, the loss of soil carbon (C), nitrogen (N) and phosphorus (P) threaten soil productivity [2] and leads to unsustainable land use in the long term. Therefore, the difficulty of soil conservation requires farmers to invest considerably in their agricultural landscapes. Attempts to implement a "green revolution" model in Africa using subsidies and inputs such as chemical fertilizers have been costly and unsustainable [3].

One affordable approach is to develop best practices for agroforestry that replenish soil fertility. These practices are based on a variety of management techniques using the ecological functions of vegetation to improve soil fertility. Trees in agroforestry parklands have a significant influence on soil organic matter and nutrient availability [4]. Trees and shrubs are an important component of smallholder farming systems and are usually used as soil organic amendments [5]. The use of green manure from tree and shrub pruning has been promoted as an alternative source of N in sub-Saharan countries [6]. The adequate use of green manure requires more information on the quality of the plant material and its nutrient release during decomposition. Despite their high biomass productivity in agroforestry systems, some important agroforestry species, such as *Vitellaria paradoxa* C.F.Gaertn., exhibit a low-litter decomposition rate [7, 8]. Yet the biomass of some leguminous trees such as

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Detarium microcarpum Guill. & Perr. are widely used as green manure for soil amendments in the Sudanian zone of West Africa, but there is a lack of knowledge about their decomposition and nutrient release.

Because of the low decomposition rates of some agroforestry species' biomass and a lack of appropriate methods for its efficient use, farmers usually burn a great quantity of litter at the beginning of the rainy season during field preparation. Consequently, litter burning leads to the loss of organic C and N through volatilization, a reduction in soil biological activity and an increased risk of nutrient loss. Innovative management approaches for leaf litter of poor quality must be developed to limit burning practices and the use of chemical fertilizers in smallholder farming systems.

The decomposition and nutrient release of the leaf litter of agroforestry species have received much attention during recent decades [4, 9, 10]. The leaf litter decomposition process depends on many factors, among which litter quality is known as one of the major drivers of organic matter degradability and decay rate [11–13]. Detailed examination of the litter quality showed that N-poor litter decomposes slowly, while N-rich litter decomposes faster [9, 10]. According to the nutrient transfer theory [14], adding N to leaf litter of poor quality may increase the decomposition rate of mixed leaf litter [7, 8, 15, 16]. The addition of exogenous N avoids N immobilization during decomposition of leaf litter of poor quality [7]. However, the addition of N to poor quality litter could have mixed effects by accelerating or slowing the decomposition rate [17]. Thus, more investigation is needed to address the knowledge gaps and uncertainty about the effect of N addition on the decomposition process of leaf litter.

Azolla africana Desv. (Azollaceae) is a water fern that has been previously documented as a biofertilizer with high agronomic potential [18]. This species has often been used to improve rice production [19, 20]. Even though the agronomic potential of *A. africana,* a natural source of N, is well documented, no information is available concerning its effect on the leaf litter decomposition process. Recent developments in agroecology require improved knowledge of nutrient cycles [21] for achieving synchrony between nutrient release from green manure decomposition and crop demand. There is a need to better understand the pattern of decomposition and nutrient release from the leaf litter of agroforestry species for improving biomass management in agroforestry systems.

The overall objective of this study was to determine the effect of mixed leaf litter of varying quality (*A. africana, D. microcarpum* and *V. paradoxa*) on their rates of decomposition and nutrient release. Specifically, this study aims:

i. To evaluate the decomposition rate of pure and mixed leaf litter of the three agroforestry species *A. africana, D. microcarpum* and *V. paradoxa*;
ii. To evaluate the effect of *A. africana* (higher quality litter) on the decomposition process of *D. microcarpum* (lower litter quality) and *V. paradoxa* leaf litter (lower quality litter); and
iii. To determine the rates of nutrient release (N, P and K) during the decomposition period.

The study focused on the decomposition pattern and nutrient release from leaf litter of contrasted quality and tested the following hypotheses:

i. The decomposition rate of litter of *A. africana* (higher litter quality) is higher than that of *D. microcarpum* (lower litter quality) and *V. paradoxa* (lower litter quality).
ii. *A. africana* increases the decomposition rate of litter of *D. microcarpum* and *V. paradoxa*.
iii. The decomposition rate of the leaf litter is correlated with nutrient release.

2 Materials and methods

2.1 Experimental site

The experimental site is located in Boura Village (W 2°30′7.2″, N 11°02′2.4″) in the southern Sudanian zone of Burkina Faso. The annual rainfall (from 2008–2017) ranged from 818 to 1030 mm with most falling during the rainy season (May to October).

The site's average minimum and maximum temperatures are 23.6 °C and 40 °C, respectively. The experiments were conducted on Luvisols in a long-term fallow site. The topsoil (0–10 cm) had a sandy texture with 9% clay, 74% sand and 16% silt. The topsoil was slightly acidic (pH = 5.8) with low total C (11.2 g kg^{-1}), total N (0.5 g kg^{-1}) and available P (2.69 mg kg^{-1}) contents. The soil C/N ratio was 22:4.

2.2 Selections of agroforestry species and leaf litter sampling

Three species were selected from the most widely used species in Sudanian agroforestry systems in West Africa: *Vitellaria paradoxa* (Gaertn. f.) (Sapotaceae), *Detarium microcarpum* Guill. & Perr. (Fabaceae) and *Azolla africana* (Desv.) R.M.K. Saunders et K. Fowler (Salviniaceae). In rice production systems, farmers use *Azolla africana*, an N-fixing water fern, as a green manure [19]. *Vitellaria paradoxa* (karité in French and shea tree in English) is one of the most common tree species in the agroforestry parklands of southern Burkina Faso [22]. *Detarium microcarpum* (Petit détar in French and tallow tree in English) is a non-N_2-fixing leguminous shrub that is widespread in the Sudanian zone. Pruned leaves of *D. microcarpum* are traditionally used by farmers as a green manure to enhance soil fertility.

Fresh leaves (5000 g) were sampled from *A. africana*, *V. paradoxa* and *D. microcarpum* in different stands in an agricultural landscape of Boura Village. Samples were selected from 50 individuals of each tree species (*V. paradoxa* and *D. microcarpum*), and 100 g of fresh leaves was randomly collected from each individual. In addition, 5000 g was collected from samples of *A. africana*. Leaves from these species were mixed to make homogenous composite samples. The samples were air-dried for one week and then oven-dried to a constant weight at 60 °C for 48 h.

2.3 Field trial design and treatments

The experiment was set up in an old fallow site using five treatments with five replications arranged in a completely randomized block design. In each block, 25 plots (1 m × 1 m) were established for the five treatments with five retrieval dates (2, 4, 6, 8 and 16 weeks) after the start of the experiment. A total of 125 litterbags were used. Thus, three treatments were established with pure leaf litter from each agroforestry species (*V. paradoxa*, *D. microcarpum* and *A. africana*). In addition to the three homogenous treatments, two categories of litter mixtures were established using an equal mass (dry weight proportion: 2.5 g + 2.5 g) of *V. paradoxa* + *A. africana* and *D. microcarpum* + *A. africana*. These treatments were designed to assess the effects of the mixture on the decomposition rate of poor quality litter. The five treatments of leaf litter tested were as follows:

T1: *A. africana.*
T2: *D. microcarpum.*
T3: *V. paradoxa.*
T4: *A. africana* + *D. microcarpum.*
T5: *A. africana* + *V. paradoxa.*

2.4 Litterbag incubation

The field experiment was conducted during the rainy season from July to November 2017 to understand the decomposition pattern of leaf applied in a similar manner to farmers' practices. Litterbags (20 cm × 20 cm) made with nylon netting with a 1 mm × 1 mm mesh size were used to assess the decomposition rate of leaf litter under field conditions. This mesh size allowed microorganisms to access the litter, but prevented the loss of small-diameter fragments. After field preparation, each litterbag containing 5 g of leaf litter was incubated at a depth of 5 cm. On each sampling date, 25 litterbags were retrieved. The remaining litter was recovered, cleaned and carefully washed to remove soil particles. These residues were air-dried for one week and then oven-dried to a constant weight at 60 °C for 48 h.

2.5 Chemical analyses

The pure litters of the agroforestry species were characterized in terms of their initial contents: total C, N, P, potassium (K) and total polyphenols. Total C was determined using the Weakley and Black method [23]. The N and P contents were measured by an autoanalyzer (Skalar, Netherlands) after mineralization by sulfuric acid and salicylic acid. The K content was determined by a flame photometer. Total polyphenols were quantified after a reaction with Folin-Ciocalteu reagent [24].

2.6 Decomposition rate

The leaf litter decomposition rate was assessed in each litterbag after retrieval. The remaining litter was then carefully cleaned and weighed. The percentage of the leaf litter dry weight that had decomposed for each species at time t, R_t, was calculated as follows:

$$R_t(\%) = \frac{M_t}{M_i} \times 100 \quad (1)$$

where M_t = the dry weight of the decomposed leaf litter at sampling time t and M_i = the initial dry weight of the leaf litter.

The decomposition rate constant (k) for each species was calculated to describe the decomposition pattern at time (t) using a single exponential model [25]:

$$M_t = M_i \times e^{-kt} \quad (2)$$

where M_t = the dry weight of the decomposed leaf litter at sampling time t and M_i = the initial dry weight of the leaf litter.

The times required to achieve 50% and 95% mass loss were calculated as: $t_{50\%} = -ln0.5/k$ and $t_{95\%} = 3/k$, respectively [25].

The effects of mixing litter from different species were investigated, focusing on the mass of whole litter (observed values) and the expected values (data from pure litter). Expected values for the mixing of pure leaf litters (1) and (2) were calculated as follows:

$$\text{Expected remaining mass (Mrep)} = \left(\frac{M1i}{M1i + M2i}\right) \times M1t + \left(\frac{M2i}{M1i + M2i}\right) \times M2t \quad (3)$$

In this equation, M_{1t} and M_{2t} are the remaining dry mass at time ***t*** in pure litterbags **1** and **2,** respectively, and M_{1i} and M_{2i} are the initial litter dry mass of these species in the mixture.

In this study, the litter of the two species in the mixture had an equal proportion ($M1i = M2i$) that allows:

$$M_{\text{rep}} = \frac{M1t + M2t}{2} \quad (4)$$

The expected remaining mass was compared with the observed remaining mass of the mixed leaf litter by running paired *t*-tests to determine the significance of deviations. To determine the strength of the litter-mixing effects, the interaction strength (%) was calculated by the following equation [26]:

$$\text{Interaction strength (\%)} = |\text{Observed values} - \text{Expected values}| \quad (5)$$

where the observed values was the remaining mass (%) found in the mixed litter bag and the expected values was calculated following equation (4).

The interaction strength was recently used in many mixed litter studies [27–30] to assess the effects of leaf mixtures on the decomposition rate.

2.7 Determination of nutrient release

The nutrient release from the decomposing leaf litter of the individual species was derived using the equation:

$$\text{Nutrients release(\%)} = \frac{C_i \times Mi - C_t \times Mt}{C_i \times Mi} \times 100 \quad (6)$$

where C_i is the initial concentration of the nutrients (N, P and K) and C_t is the concentration of the nutrients (N, P and K) in the decomposing leaf litter at sampling time t.

The single exponential model was also fitted to describe the nutrient release patterns and calculate their constant (k) rate from the leaf litter of the three agroforestry species.

Statistical differences of initial nutrient concentrations among the litter types were examined by performing one-way analysis of variance (ANOVA) at $p < 0.05$. Two-way ANOVA using the general linear model (GLM) was performed to determine the effect of treatments and sampling time on the means of the remaining mass [31]. The remaining mass was the dependent variable, while leaf litter and sampling time were independent variables. Where significant differences were observed, a post-hoc Tukey's comparison test was used to separate all the means.

Paired t-tests were used to compare the decomposition rate constant k between the pure litters and the mixed litter and the nutrients release rate from the agroforestry species' leaf litter.

Then ANOVA was run to determine the dynamic of the interaction strength during sampling time. The linear relationship between the original litter mass and the nutrient content was analyzed using Pearson's correlation coefficient. All the statistical analyses were performed using R.3.6.1.

3 Results

3.1 Initial litter characteristics

The initial chemical contents (C, N, P and K) of the leaf litter of the three species were significantly different (Table 1). *Azolla africana* had the lowest C/N ratio, P, and total polyphenol values and the highest N and K contents. There were also significant differences ($p < 0.05$) in the litter of *D. microcarpum* and *V. paradoxa* for all initial nutrient contents apart from N (Table 1). *Vitellaria paradoxa* had the highest C/N ratio of the three species. Based on their chemical composition, *A. africana* leaf litter had the

Table 1 Chemical composition of initial leaves of *Azolla africana, Detarium microcarpum* and *Vitellaria paradoxa* (Mean values Standard ± Deviation)**.** Values with the same letters in the same line are not significantly different

	Azolla africana	*Detarium microcarpum*	*Vitellaria paradoxa*
N(gkg^{-1})	19.45 ± 1.71^{b}	13.97 ± 0.82^{a}	11.23 ± 0.48^{a}
P(gkg^{-1})	0.93 ± 0.05^{a}	1.56 ± 0.06^{c}	1.11 ± 0.06^{b}
K(gkg^{-1})	26.18 ± 0.48^{c}	10.44 ± 0.42^{a}	14.76 ± 1.21^{b}
C (gkg^{-1})	378.89 ± 1.01^{a}	558.35 ± 0.22^{c}	552.74 ± 0.21^{b}
C/N	19.57 ± 1.67^{a}	40.06 ± 2.36^{b}	49.27 ± 2.12^{c}
C/P	410.16 ± 23.33^{a}	358.51 ± 17.69^{a}	496.95 ± 25.51^{b}
Polyphenols (%)	16.04 ± 0.48^{a}	27.48 ± 1.04^{b}	38.12 ± 0.68^{c}

highest nutrient contents, while *V. paradoxa* litter had the lowest nutrient contents.

3.2 Decomposition dynamics of leaf litter

The mass loss of leaf litter was significantly different between the leaf litter treatments and the sampling time (Table 2). The rate of mass loss was significantly higher (F = 130.888, p-value < 2.2e-16) in the early phase of decomposition than the last phase (Fig. 1). The GLM of ANOVA showed that the interaction between treatments and sampling time also significantly affected the leaf litter decomposition (p-value < 0.001). The multiple comparison test showed that the litter of *A. africana* decomposed faster than that of *D. microcarpum* and *V. paradoxa* (Table 3). The decomposition of mixed litter was significantly faster than that of pure *D. microcarpum* and *V. paradoxa* litter and slower than that of pure *A. africana* litter (Table 3). No significant difference was found between the remaining mass of pure *D. microcarpum* and *V. paradoxa* (p-value > 0.05).

Table 2 Effect of leaf litter type and sampling time of the remaining mass

Variables	Sum square	Degree of freedom	*F* value	Pr(> *F*)
Litter	45,379	4	82.0664	< 2.2E–16***
Time	90,469	5	130.8876	< 2.2E–16***
Litter × Time	11,615	20	4.2009	0.0000003595***

****P* < 0.001

The half stage of decomposition (0–50% mass loss) lasted a week for *A. africana,* and 6 weeks for *A. africana* + *V. paradoxa* and for *A. africana* + *D. microcarpum* (Table 4). The pure litters of *V. paradoxa* and *D. microcarpum* decomposed to 50% mass loss after 9 weeks. After 4 weeks of incubation, there was a significant difference between the decomposition rate (*k*) of leaf litter among species (F = 8.7196, *p*-value < 0.05). The *A. africana* decomposition rate was highest (*k* = 0.406 ± 0.296 week-1), followed by those of its mixture with *V. paradoxa* (*k* = 0.248 ± 0.065 week-1) and with *D. microcarpum* (*k* = 0.137 ± 0.097 week-1). The lowest decay rates were those of pure *D. microcarpum* (*k* = 0.094 ± 0.020) and *V. paradoxa* (0.075 ± 0.007 week-1) litter. After 16 weeks, all *A. africana* litter had decomposed. At this time, the paired t-test revealed that the overall decomposition rate of mixed litters was higher than those of pure litters of both *V. paradoxa and D. microcarpum* (t = 2.7081, df = 10.928, p-value = 0.02047). The trend of the decomposition rate of leaf litter was ordered from quickest to slowest, as follows

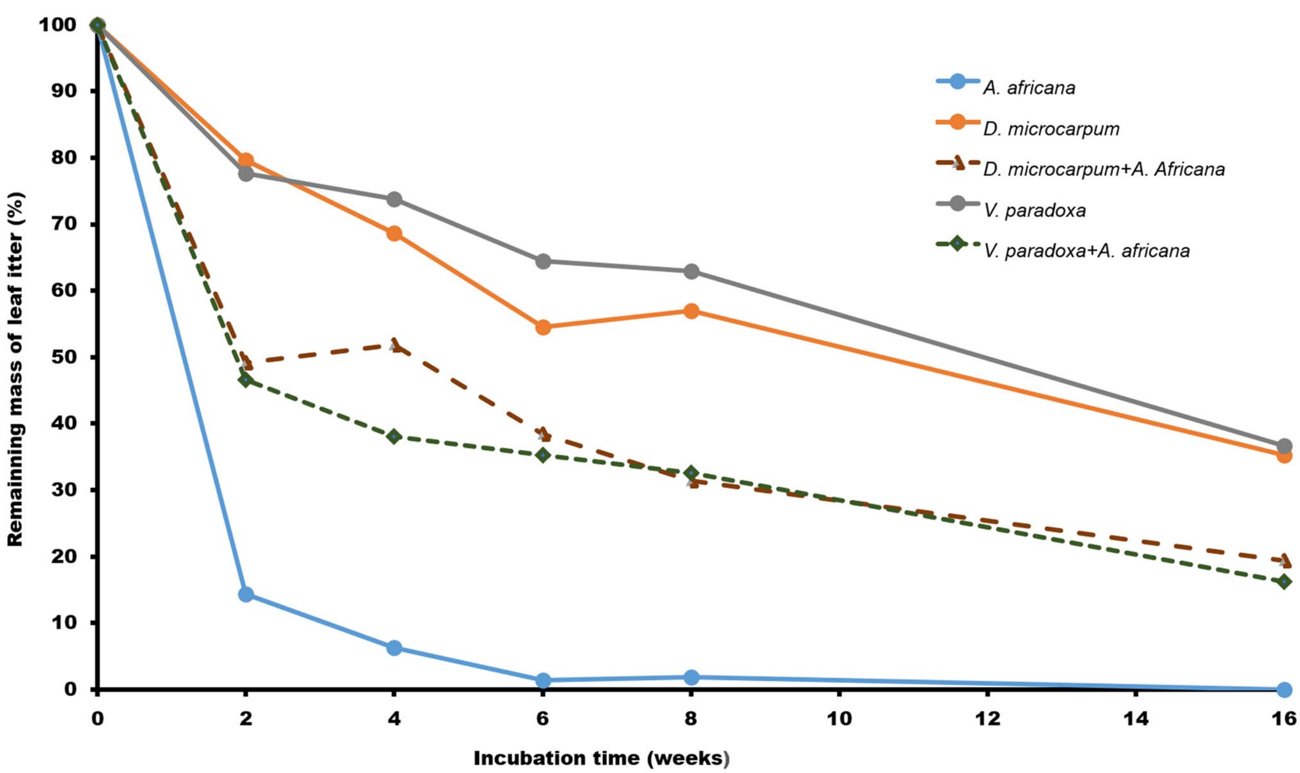


Fig. 1 Remaining mass (%) of pure litter of *Azolla africana*, *Detarium microcarpum* and *Vitellaria paradoxa* and their mixture: *Azolla africana* + *Vitellaria paradoxa and Azolla africana* + *Detarium microcarpum*

Table 3 Comparison of remaining mass of the different leaf litter of *A. africana* (A), *D. microcarpum* (D) *and V. paradoxa* (V) and mixed leaf litters of *A. africana* + *D. microcarpum* (AD) and *A. africana* + *V. paradoxa* (AV). Significant at 5% (*); ns: non-Significant at 5%

Leaf litter	Estimate	SE	t value	Pr(>|t|)
D—A	45.189	7.387	6.118	< 0.001***
AD—A	27.726	7.387	3.754	0.00233**
V—A	48.610	7.387	6.581	< 0.001***
AV—A	24.154	7.387	3.270	0.01149*
AD—D	− 17.463	7.387	− 2.364	0.13122 ns
V—D	3.421	7.387	0.463	0.99046 ns
AV—D	− 21.035	7.387	− 2.848	0.03975*
V—AD	20.884	7.387	2.827	0.04206*
AV—AD	− 3.572	7.387	− 0.484	0.98876 ns
AV—V	− 24.456	7.387	− 3.311	0.01016*

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

ns, not significant

(Table 4): *A. africana* > *A. africana* + *V. paradoxa* > *A. africana* + *D. microcarpum* > *D. microcarpum* ≥ *V. paradoxa.*

3.3 Interaction dynamics of mixed leaf litter

In the mixed leaf litters, the observed values for the remaining mass were lower than the expected values. There was a significant difference between the observed and expected values of mass decay for *A. africana* + *V. paradoxa* (t = -10.746, df = 24, p-value = 1.184e-10). In the mixed *A. africana* + *D. microcarpum* litter, the expected remaining mass was also significantly higher than the observed remaining mass (t = -8.833, df = 24, p-value < 0.005). The interaction strength was high in the first four weeks and significantly (p-value < 0.005) decreased with incubation time, while there was no significant difference found between the two mixed litter treatments (F = 0.80026, df = 47.887, p-value = 0.3755).

3.4 Nutrient release during leaf litter decomposition

The release of K and P in the decomposing leaf litter decreased during the early stage (0–8 weeks). For all three species, K and P were quickly released (Fig. 2) at this time. Nitrogen was rapidly released during the first month (0–4 weeks) for all the species and gradually became immobilized over the rest of the incubation time. The *k* values of the release rates of K and P were significantly different among species. However, there was no significant difference in the remaining N between the leaf litter of *D. microcarpum* and *V. paradoxa*. After 16 weeks of incubation, P and N was not released, and there were significant differences in the nutrient release rate from leaf litter of *D. microcarpum* and *V. paradoxa* (Table 5), except for k_{N}, t_{N50} and t_{N95}.

The nutrient release constant *k* values of the leaf litter were significantly different among species. The release patterns for *D. microcarpum* and *V. paradoxa* were significantly different for K and P, but not for N (Table 5). *Detarium microcarpum* released P three times faster than *V. paradoxa,* and the half released point of the *D. microcarpum* P content was reached in 13.5 weeks. The general trend of nutrient release was K > P > N for *D. microcarpum* and *V. paradoxa*. The half life of all nutrients was significantly shorter for K and longer for P. Notably, 90% of K was released in 12 weeks. There was high correlation between the remaining mass and K content for the leaf litter of all the species (Table 6). However, the N and P contents were significantly correlated to the remaining mass of *V. paradoxa* and *D. microcarpum*, respectively.

4 Discussion

4.1 Effect of initial leaf chemistry on the decomposition process

Contrary to expectations, this study did not find a significant difference between the N content of *D. microcarpum* and *V. paradoxa* leaves. This result suggests that *D.*

Table 4 Weekly decomposition rate constants, *k* (Mean values ± SD) and time required for 50% and 95% of mass loss for pure and mixed leaf litter

Litter type	k (week-1)	Adjusted R2	t50 (week)	t95 (week)
Azolla africana	0.41 ± 0.30	0.30	1.70	7.39
Detarium microcarpum	0.08 ± 0.05	0.63	9.24	40
Vitellaria paradoxa	0.07 ± 0.04	0.79	9.76	42.25
Azolla africana + *Detarium microcarpum*	0.10 ± 0.01	0.49	6.73	29.12
Azolla africana + *Vitellaria paradoxa*	0.11 ± 0.01	0.54	6.08	26.31

microcarpum is a non-N_2-fixing leguminous tree [32] with litter quality that matches that of *V. paradoxa*. This similarity in the litter quality of these two agroforestry species resulted in similar decomposition rates when they were incubated with *A. africana* or alone. These findings were in contrast to those of Bayala et al. [7] who reported differences in N content and decomposition rates between leaves of Néré (a non-N_2-fixing leguminous tree) and Karité (*V. paradoxa*) in Burkina Faso. These differences in decomposition rates of leaf litter between leguminous trees and *V. paradoxa* find in previous studies [8, 33] can only be attributable to differences in the chemical quality of leaf litter. In line with previous studies [9, 13], we found that litter quality is one of the major drivers of organic matter decay rates**.**

In our study, *A. africana* decomposed much faster than *D. microcarpum* and *V. paradoxa*. The leaves of *A. africana* were initially characterized by the highest N and P contents and the lowest C/N ratios which emphasized its high quality and faster decomposability. Many studies have already noted the crucial role of leaf litter chemical quality in the decomposition process [34]. Likewise, the lower quality of *D. microcarpum* and *V. paradoxa* leaf litter in terms of their N and P contents and C/N ratios led to their lower decay rates. The poor leaf quality of *V. paradoxa* has been previously documented [8]. The role of stoichiometric parameters (C/N ratio and C/P ratio) in organic matter decomposition processes has been widely reported [13, 35, 36]. A high N content and low C content in leaves increases organic matter decomposability. Nitrogen and P are important sources of energy for soil microorganisms [37]. Phosphorus is used by soil microorganisms for the synthesis of ATP, RNA, DNA and phospholipids, while N is an essential component of proteins. Leaf litter resource quality and C/N/P stoichiometry influence soil microbial activity and strongly affect the decomposition rate [37, 38]. The rapid rates of decay as reported in the present study may also be linked to termites and earthworms which were present in the soil and have likely hastened the leaf litter decomposition rates.

4.2 Effect of *Azolla africana* on the decomposition of leaf litter of poor quality

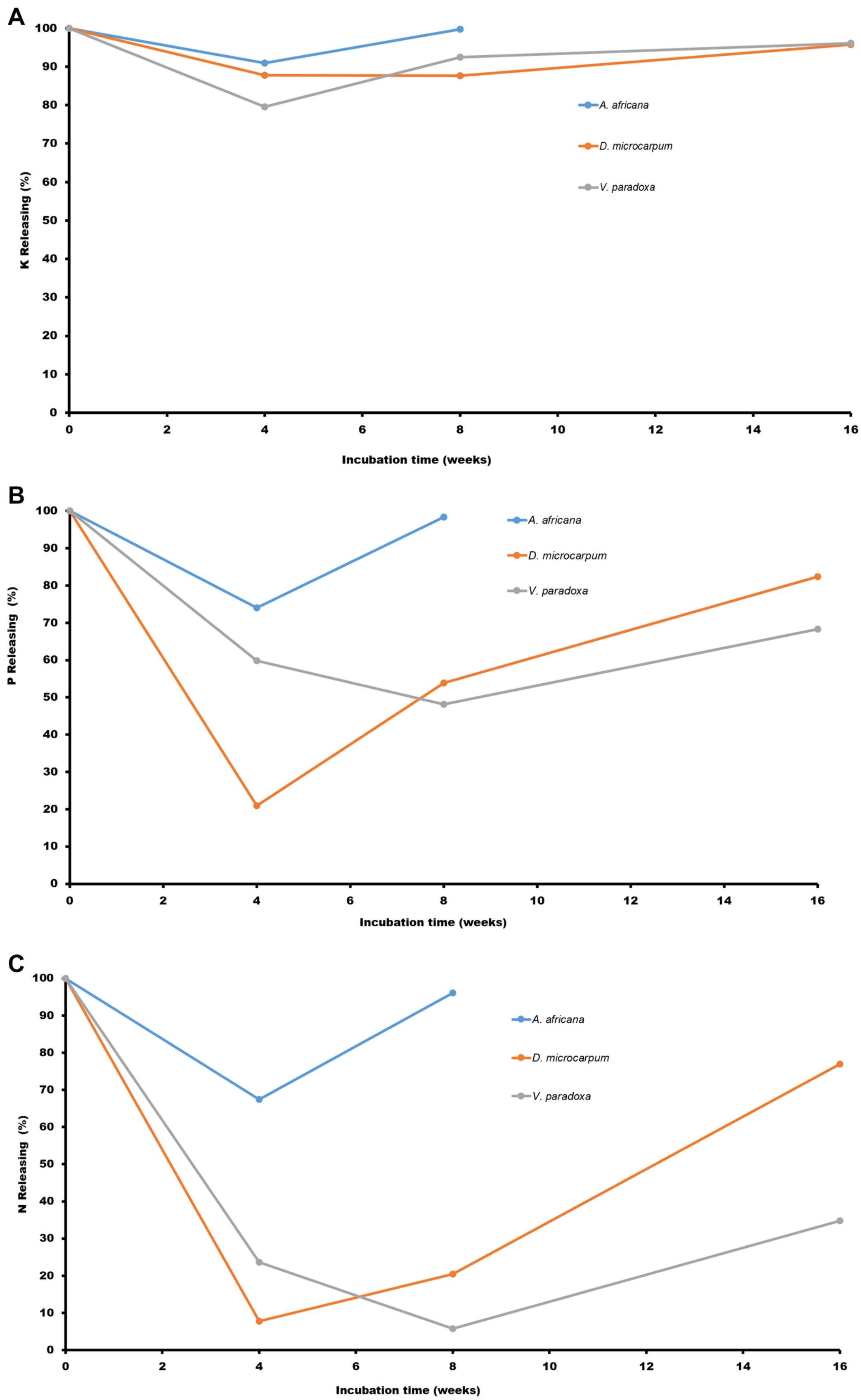
The decomposition rate was related to the leaf chemical composition when litter was incubated alone. However, the decomposition rates of *D. microcarpum* and *V. paradoxa* were similar when they were incubated with *A. africana* or alone. These results can be explained by the involvement of the same *A. africana* decomposers in the two mixed leaf litter treatments. According to Song et al., [12], there are specific decomposer communities for leaf litters of different quality.

The expected mass loss was significantly higher than the observed mass loss. These findings are supported by many studies that have reported a greater deviation between the observed and expected mass of leaf litter when the litters have contrasting quality [8, 27, 28]. Most likely, the presence of *A. africana* in the mixture led to the presence of many decomposers because of the low values for the C/N ratio and the high values of N in the mixed litter.

In the mixed litter, the interaction strength between *A. africana* and *V. paradoxa* were slightly higher than that between *A. africana* and *D. microcarpum*. Thus, the synergistic effect of *A. africana* in mixture with the litter of both species was similar. In these two mixtures, non-additive effects and synergistic interactions have been reported. These findings suggest that N-rich leaf litter (*A. africana*) may transfer nutrients to N-poor litter (*V. paradoxa*), which increases the decomposition rate [8, 14, 30, 39]. This evidence is supported by a study in northern Canada [40] that found the decomposition rate was increased only in a mixture containing N-rich speckled alder leaves, and was conversely inhibited by mixing yellow birch leaves with red maple leaves. Several mechanisms with a set of complex biological, physical and chemical processes have been suggested to explain synergistic interactions in decomposing leaf litter of different qualities [10, 16, 41]. According to many studies [42, 43], there is an alteration in the total leaf surface in the mixture because of the changing environment. Litter mixtures are presumed to create microhabitats that enhance both the abundance and activity of decomposer communities [9, 43]. Another explanation for these interaction effects is provided by evidence of nutrient transfer from higher-quality litter to lower quality litter [9, 14, 44].

4.3 Nutrient dynamics during the decomposition process

Nutrient release patterns during leaf litter decomposition were consistently different among the different species and nutrients. During decomposition, the N and P concentrations of the leaf litters increased after 8 weeks of incubation. It is generally found that N and P concentrations increase after the early stage of litter decay [45, 46]. Higher concentrations of N and P in decomposing leaf litter may be linked to C mineralization leading to enrichment of N and P, or suggest the addition of exogenous sources of N and P to litter [8]. Furthermore, microorganisms resort to soil N because of N limitations during the decomposition of litter with a high C/N ratio [37, 45, 47]. During the decomposition of leaf litter with a high C/N ratio, a


A
B
C
K Releasing (%)
P Releasing (%)
N Releasing (%)
Incubation time (weeks)
A. africana
D. microcarpum
V. paradoxa

◂**Fig. 2** **a** Potassium (K) releasing during leaf litter decomposition of *Azolla africana*, *Detarium microcarpum* and *Vitellaria paradoxa,* **b** Phosphorus (P) releasing during leaf litter decomposition of *Azolla africana*, *Detarium microcarpum* and *Vitellaria paradoxa,* **c** Nitrogen (N) releasing during leaf litter decomposition of *Azolla africana*, *Detarium microcarpum* and *Vitellaria paradoxa*

substantial amount of the N and P in litter is bound in complex compounds that are less available to decomposers.

Potassium had the highest release rate because it exists in ionic form in the cell sap vacuole and is not a structural component of plant tissues [45]. Thus, K is released in accordance with the gradual process of leaching during the decomposition of plant materials. A similar result of a high K release rate was found in an investigation of green manure from 12 plant species in a tropical agroecosystem in Colombia [48]. In our study, the release of K was correlated with mass loss in all the species, while the N and P release was significantly correlated with mass loss in *D. microcarpum* and *V. paradoxa*, respectively. These results suggest that the influence of litter mass loss on nutrient dynamic patterns depends on the species and nutrient type.

4.4 Implications for agroecological fertilization

The decomposition of *A. africana* leaf litter was faster than that of the other two species. Fifty percent of the *A. africana* litter decomposed in less than 2 weeks of incubation. In another study, after 2 months of incubation, the remaining mass of other agroforestry species such as *Gliricidia sepium* (Jacq) Kunth ex Walp and *Leucaena leucocephala* (Lam) De Wit. was approximately 60% [49]. One of the main findings of our study is that mixing litter can increase the decomposition rate of poor quality litter by at least 66%, according to the *k* values found for the litter mixtures. This finding suggests that *A. africana* could be used to improve the decomposition of low-quality green manures. An important issue emerging from these findings is that 50% of the mixed litter decomposed in 6 weeks. These results must be considered when mixing *A. africana* with plant material of poor quality for achieving enhanced litter decomposition. Therefore, due to its high quality, *A. africana* may be an important source of low-cost fertilizer in tropical smallholder farming systems. Its agronomic potential in rice production has been reported in southern Burkina Faso [19] and other parts of the world [18, 20]. However, the potential of *A. africana* to improve the decomposition of leaf litter of poor quality has not yet been documented before the present study. In the tropical zone of West Africa, the improvement of soil physical properties and nutrient supply are great challenges that must be met to strengthen crop production in the region [1]. The plant leaf litters investigated in this study are affordable materials that can be readily used for agro ecological fertilization [21, 50]. Many studies have highlighted the role of local plants as low-cost fertilizers as an alternative to chemical fertilizers [7, 51–54]. Thus, all of the plant materials studied here could be used in combination for best achieving soil physical protection and synchrony between litter decomposition and crop demand [7].

5 Conclusion

This study determined the decomposition rates and nutrient release patterns from pure and mixed leaf litter of three agroforestry species common in West Africa (*Vitellaria paradoxa*, *Detarium microcarpum* and *Azolla africana*) under field conditions. It was found that the decomposition rate was much higher when the leaf litter C/N ratio was lower. Nutrient release was significantly correlated with leaf litter mass decay and degradability. At the early stage of leaf litter incubation, the rates of decomposition and nutrient release were higher than those at the final stage. Nutrient release rates, especially for K and P, were different between *D. microcarpum* and *V. paradoxa*. The decomposition of *D. microcarpum* was influenced by the P content in the leaves, while that of *V. paradoxa* was influenced by the N components in the leaves. *Detarium microcarpum* leaf litter decomposition was not statistically faster than *V. paradoxa* leaf litter. *Azolla africana* is a good fertilizer but it decomposes rapidly. The addition of *A. africana* increases the decomposition rate and the release of necessary nutrients from the leaf litter of both *D. microcarpum* and *V. paradoxa*. Mixing *A. africana* with other species' leaf litter can be an innovative management technique for nutrient recycling and soil organic carbon addition. *Azolla africana*, with its high levels of N and P, could be used to develop sustainable best practice agro ecological fertilization systems by improving the decomposition of poorer quality plant materials and removing the need for the burning practices commonly applied by farmers. Finally, the successful transition to agro ecological systems needs

Table 5 Nutrient released rates *k* (week^{-1}) and time required for different levels ($\mathbf{t_{50}}$ and $\mathbf{t_{90}}$) for N, P and K after 16 weeks of incubation

Nutrient release pattern	*Detarium microcarpum*	*Vitellaria paradoxa*
k_N	0.0205 ± 0.080[a]	0.069 ± 0.019[a]
k_P	0.057 ± 0.023[a]	0.0208 ± 0.009[b]
k_K	0.248 ± 0.0132[a]	0.284 ± 0.059[b]
t_{N50}	21.6 ± 29.6[a]	10.5 ± 2.5[a]
t_{P50}	13.6 ± 5.9[a]	38.0 ± 16.5[b]
t_{K50}	2.8 ± 0.2[a]	2.5 ± 0.5[b]
t_{N95}	93.5 ± 127.8[a]	45.4 ± 10.9[a]
t_{P95}	58.7 ± 25.6[a]	164.5 ± 71.4[b]
t_{K95}	12.1 ± 0.7[a]	10.9 ± 2.3[b]

Values with the same letter in the same line are not significantly different ($P < 5\%$). Values with different letters in the same line are significantly different

Table 6 Pearson's correlation (r) between leaf litter remaining mass and nutrient content (N, P, K)

Nutrient	Remaining mass of leaf litter		
	Azolla africana	*Detarium microcarpum*	*Vitellaria paradoxa*
N	− 0.2180 ns	− 0.214 ns	− 0.823***
P	− 0.344 ns	0.717***	0.402 ns
K	0.916***	0.824***	0.779***

*Significant at 5%

ns, non-significant at 5%

considerable effort to develop best management practices for nutrient recycling in agricultural landscapes.

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Data availability and material (data transparency) The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Consent for publication This current work has not been published previously, is not under consideration for publication elsewhere, its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright holder.

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