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Decomposition and nutrient release from leaves of some common agroforestry tree/shrub species of Sahelian West Africa

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Abstract

Foliar inputs from indigenous agroforestry trees/shrubs provide organic matter and nutrients to sustain crop production in the West African Sahelian region. This study aims at monitoring the decomposition and nutrients release of leafy biomass of selected agroforestry tree and shrub species. From Mali and Burkina Faso, fresh leaves were collected from leguminous trees (*Faidherbia albida* (Delile) A. Chev., *Pterocarpus lucens* Lepr.) and non-leguminous trees (*Vitellaria paradoxa* C.F. Gaertn., *Khaya senegalensis* (Desr.) A. Juss.) and from Senegal, fresh leaves were obtained from leguminous trees (*Faidherbia albida* (Delile) A. Chev., *Pterocarpus lucens* Lepr. and *Piliostigma reticulatum* (DC.) Hochst.) and non-leguminous tree *Guiera senegalensis* J.F. Gmel. The leaf samples collected during the dry and rainy seasons were deployed for decomposition and nutrient release experiments using the litter bag technique. Average decomposition rate for this study was 0.23 k week⁻¹ while the rate of decomposition was 155 % higher in the rainy season over the dry season. Average decomposition rate of leguminous tree and shrub leaves was 1.4-folds greater than that of non-leguminous counterparts. To optimize the synchronization of nutrient release from green manure with crop nutrient demands, manure should be applied considering seasonal and species effects

Keywords: Green manure, nutrient cycling, soil fertility, Litter quality, shade trees, tree species, Season

Introduction

Subsistence agriculture employs 80% of the population in the Sahelian Region of West Africa ¹ thereby serving as the main source of food production in the region. Due to inherently poor soil fertility ², extended drought periods ^{3,4} and rampant population growth,

the Sahel is recurrently plagued by food insecurity¹. The poor soils are subjected to further nutrient losses through crop harvest whereby extracted nutrients are insufficiently replaced due to unavailability and high cost of inorganic fertilizers^{5,6}. Farmers in this region traditionally use leafy biomass of various trees and shrubs for improving soil fertility and mulching to retain soil moisture and catch Harmattan dust⁷⁻⁹. Commonly used species include *Vitellaria paradoxa* C.F Gaetn., *Parkia biglobosa* (Jacq.) R.Br. ex G. Don^{2,10}, *Faidherbia albida* (Del.) A. Chev.^{2,11}, *Piliostigma reticulatum* (DC.) Hochst. and *Guiera senegalensis* J.F. Gmel.^{12,13}. Hence, there is great interest in using green manure in the form of pruned tree and/or shrub leaves as a major nutrient source in small-scale low external input agricultural systems^{14,15}. Upon application, decomposition and nutrient release processes transfer nutrients stored within this leafy biomass into the soil for crop use. Hereby decomposition and nutrient release processes are regulated by climate¹⁶, soil properties¹⁷, and biomass quality such as chemical properties of leafy biomass^{14,18}. Studies by^{14,19,20} highlight that decomposition of leafy biomass is significantly faster during the rainy season than during the dry season. High moisture levels during the former increase soil organism activity, leading to faster mineralisation of organic matter and concomitant release of nutrients¹⁹⁻²². In consequence, nitrogen (N) and phosphorus (P) concentrations of tree leaves in Ethiopia²³ and Nigeria¹⁹ were reported to increase during the rainy season reflecting an improved nutrient availability by accelerated litter decomposition and mineralization. Some studies found higher K and Ca concentrations in tree leaves in the dry season than in the rainy season^{24,25}, which may result from physiological adaptation to drought and/or dust depositions from the Sahara desert^{25,26}. In addition, leaf nutrient composition is also influenced by plant species, whereby nitrogen fixing leguminous trees, such as *F. albida*, *P. reticulatum*, and *Gliricidia sepium* (Jacq) Kunth ex. Walp, generally have higher N concentrations than non-fixing species. This results in lower C:N ratios of leaves, which is more favourable for microbial degradation. Previous works conducted in Nigeria²⁷ and Burkina Faso¹¹ found decomposition to be faster for leguminous trees compared to non-leguminous ones. On the other hand, mineralization of leafy biomass with low N concentration but high lignin concentration may lead to N immobilization, whereby soil microbes utilize nutrients from the soil solution and deplete available soil nutrients^{28,29}. Repeatedly, secondary metabolites such as lignin and polyphenols were found to retard the decomposition rate of tree leaves^{28,30-33}. Such polyphenols, which are found in many sub-Saharan tree/shrub species like *F. albida* and *V. paradoxa*, have the ability to form complexes with N containing compounds, which subsequently slows down the N mineralization of polyphenol-rich leafy biomass³⁰. Despite great interest in the use of tree leafy biomass as a nutrient source, decomposition and nutrient release studies of commonly used tree leafy biomass from the Sahelian region are few. Understanding the rate of leafy biomass decomposition and nutrient release is key for developing small scale low external input agricultural systems, where nutrient release is synchronized to crop demand for an efficient nutrient utilization. Hence this study aims to: (i) assess the seasonal variation in the chemical properties of leafy biomass from different tree and shrub leaves, (ii) investigate how seasonal variability influences the decomposition and nutrient release patterns of leafy biomass from different tree and shrub leaves, and (iii) examine the variation in decomposition and nutrient release patterns among different tree and shrub types. It hypothesises that: (i) the initial

chemical properties of different tree/shrub leaves are different in the dry and rainy season; (ii) decomposition and nutrient release is faster during the rainy season than in the dry season, (iii) decomposition and nutrients release are greater for leguminous tree/shrub (*F. albida*, *Pterocarpus lucens* Lepr. Ex Guill. & Perr. and *P. reticulatum*) than for non-leguminous (*Khaya senegalensis* (Desr.), *Guiera senegalensis* JF Gmel. and *V. paradoxa*).

Results

Initial chemical properties of tree and shrub leaves

There was significant interaction ($p < 0.05$) between country and leaf type for N, P, C/N ratio, and total phenols (Supplementary Table S1). Nutrient concentrations of collected leaves were similar across countries, whereas N, P, and Mg concentrations of leguminous trees/shrubs were 73%, 85% and 38%, respectively, higher ($p < 0.05$) than concentrations in non-leguminous counterparts. In contrast, phenol concentrations in non-leguminous trees/shrubs were two-fold higher ($p < 0.05$) than those in leguminous trees/shrubs. Seasonality influenced nutrient concentrations with the dry season leading to 23% and 13% lower ($p < 0.05$) K and Mg concentrations in leaves than the rainy season (Supplementary Table S2). Phenol concentrations on the other hand were 37% lower ($p < 0.05$) in the rainy season than in the dry season.

In Senegal, *P. lucens* had the highest measured nutrient concentrations compared with the other species, and also the highest concentration of condensed tannins (Table 1). *P. lucens* had higher 55% higher N ($p < 0.01$), 21% higher P ($p = 0.03$), 38% higher K ($p = 0.04$), and 106% higher Mg ($p = 0.04$) concentrations than the average of the other species, resulting in a 1.5-fold lower C/N ratio than the other species. But also, it also had 319% higher CT concentrations than the average of *F. albida*, *G. senegalensis*, *F. albida* and *P. reticulatum*. For these three species C/N ratios were relatively similar but whereas CT concentrations differed. Condensed tannin concentration in *F. albida* was 12.7-times higher than that in *P. reticulatum*. Total phenol concentration in *G. senegalensis* was 10%, 29% and 70% higher ($p < 0.01$) than in *F. albida*, *P. lucens*, and *P. reticulatum*, respectively. However, the concentration of condensed tannin in *P. lucens* initial leaves, was 36-times greater ($p < 0.01$) than the lowest concentration in *P. reticulatum*.

Table 1. Initial chemical properties of different trees/shrubs leaves used for the decomposition study in Dahra, Sahelian zone of Senegal (n = 3)

For dry season Mali, nutrient concentrations in tree and shrub species differed among each another. While N, P, and K concentrations and C/N ratios of *F. albida*, *K. senegalensis*, did not differ significantly across seasons, *P. lucens* did (Table 2). *F. albida* had the highest N and P concentrations, which were 82% and 34% respectively, higher ($p < 0.01$) than the average of the other tree and shrub species while its K ($p < 0.01$) and CT concentrations ($p < 0.01$) and the C/N ratio ($p < 0.01$) were 21%, 51% and 41%, respectively lower than the average of other tree/shrub species. During the rainy season, average N concentration of *K. senegalensis* and *V. paradoxa* was 56% lower ($p < 0.01$) than the average of *F. albida* and *P. lucens*. Phosphorus concentration of *P. lucens* in the rainy season was 2-times greater than its P concentration in the dry season. In the dry season, the Mg concentration in *P. lucens* was 1.8-folds lower ($p < 0.01$) than that of *V. paradoxa*. In the rainy season, Mg concentration in *K. senegalensis* was 2-folds lower ($p < 0.01$) than the average of *P. lucens* and *V. paradoxa*.

Total phenol concentration in *V. paradoxa* was 68% and 271% higher ($p < 0.01$) than the averages of the other trees/shrubs species in the dry and rainy season, respectively. In both dry and rainy season, condensed tannins concentration was 2-times higher ($p < 0.01$) in *K. senegalensis* than the average of the other tree/shrub species.

Table 2. Initial chemical properties of different trees/shrubs leaves used for the decomposition study in Koulikoro, Sudano-Sahelian zone of Mali (n = 3)

In Burkina Faso in both, the rainy and the dry season, N, and P concentrations in *P. lucens* leaves were higher ($p < 0.01$) than in those of *F. albida*, *K. senegalensis*, and *V. paradoxa* (Table 3). Contrarily, total phenol concentrations in *V. paradoxa* leaves during both, the dry and rainy seasons were 48% and 304%, respectively higher ($p < 0.01$) than in the average of other tree and shrub species. Average P concentration for all the other leaves in the dry and rainy season was 5.5-times lower ($p < 0.01$) than P concentration in *P. lucens* in the rainy season. Whereas C/N ratio in both dry and rainy season in *P. lucens* leaves were 1.7-fold and 1.8-fold, respectively lower ($p < 0.01$) than in the average of the other tree and shrub species, its CT concentrations were 76% and 155% higher ($p < 0.01$) than that of the average CT concentration of the other tree and shrub species in both, the dry and rainy, respectively. Average Mg concentration of *F. albida* and *K. senegalensis* in the dry season was 2-fold lower than Mg concentration in *F. albida* in the rainy season.

Table 3. Initial chemical properties of different trees/shrubs leaves used for the decomposition study in Saria, Sudano-Sahelian zone of Burkina Faso (n = 3)

Decomposition and nutrient release rates

The decomposition of leafy biomass was fastest during the initial 4 weeks after placement in the soil, whereby the decline in DM was considerably slower in Senegal compared with Mali and Burkina Faso. In both Mali and Burkina Faso, the total leaf DM disappeared from the litterbags after 15 weeks in the rainy season and after 32 weeks in the dry season, respectively.

In Senegal, decomposing leaves lost on average 30% of their initial dry weight in the first four weeks after placement (Fig. 1a and Supplementary Fig. S1). At weeks 2, 4, and 8 remaining DM of *G. senegalensis* were 26%, 30%, and 33%, respectively higher ($p < 0.05$) than those of *F. albida*. At 52 weeks after placement DM losses of *F. albida* and *P. lucens* were 46% and 51%, respectively, higher ($p < 0.01$) than that of *G. senegalensis*. In Mali, leaves lost 70% of their initial dry weight within the first four weeks after litterbag placement in the rainy season (Fig. 1b and Supplementary Fig. S2), which was two-folds greater than losses in the dry season (Fig. 1c). In the rainy season at weeks 2 and 4, *F. albida* DM losses were 19% and 38%, respectively, higher ($p < 0.05$) than losses of *K. senegalensis*. In the dry season, *P. lucens* DM losses at 4 weeks after placement was 376% higher ($p < 0.05$) than that of *K. senegalensis*. At 8 and 16 weeks, DM losses of *K. senegalensis* were 58% and 60%, respectively, lower ($p < 0.05$) than for *F. albida*, and 56% and 55%, respectively, lower than for *P. lucens*. In Burkina Faso, on average 30% of initial dry weight of the decomposing

leaves were lost during the first four weeks for dry season (Fig. 1d and Supplementary Fig. S3), which was 61% lower than in the rainy season (Fig. 1e). At 2 weeks after leaf placement DM losses of *F. albida* and *P. lucens* were 45% and 60% higher ($p < 0.01$) than those of *K. senegalensis* in dry season. Similarly, at 4 and 8-weeks DM losses of *K. senegalensis* were 24% and 27%, respectively, lower ($p < 0.01$) than for *P. lucens* in the rainy season. At 16 weeks after leaf placement in dry season, *P. lucens* DM losses was 363% higher ($p < 0.01$) than that of *K. senegalensis*.

Figure 1 Decay patterns of different tree/shrub leaves after 52 weeks in litterbags placed in soil across season in Dahra in the Sahelian zone of Louga in Senegal, Katibougou and Saria in the Sudano-Sahelian zone of Koulikoro and West Central in Mali and Burkina Faso respectively. Error bars indicate $\pm$ one standard error of mean ($n=5$)

In Senegal, decomposition rate and release rates of N and P were significantly higher in leguminous species compared with non-legume species, whereas for K release rate constant were in a similar range except for *P. reticulatum* (Table 4 and Supplementary Table S6). The decomposition rate constant k of the legume species *F. albida* and *P. lucens* were by 100% higher than k of non-legume species *G. senegalensis* and *P. reticulatum* ($p = 0.02$). Similarly, average N release constant by *G. senegalensis* and *P. reticulatum* were 67% and 50% lower ($p < 0.01$) than of *F. albida* and *P. lucens*, respectively. Phosphorous release by *F. albida* and *P. lucens* were 200% and 100%, respectively higher ($p = 0.04$) than the average of *G. senegalensis* and *P. reticulatum*. Potassium release constant of *P. reticulatum* was 62%, 58%, and 55% lower ($p = 0.03$) than of *F. albida*, *P. lucens* and *G. senegalensis*, respectively.

Table 4. Decomposition rate (mineralization rate constants k : % day⁻¹) of leaves of leguminous trees/shrubs (*F. albida*, *P. lucens* and *P. reticulatum*) and non-leguminous (*G. senegalensis*) after 52 weeks in litterbags placed in soil during rainy season in Dahra in the Sahelian zone of Louga in Senegal ($n=5$).

Overall, leguminous tree/shrub species (*F. albida* and *P. lucens*) had higher decomposition rate k and key nutrient release (N and P) compared with non-leguminous tree species (*K. senegalensis* and *V. paradoxa*), especially during the rainy season, in both Mali and Burkina Faso. Though non-leguminous showed slower decomposition and lower N and P release, they were comparative in their K release, particularly during the rainy season.

In Mali, the trees/shrub leaves decomposition rate k was significantly influenced by season ($p < 0.01$) and species ($p = 0.03$). While N and P release rates were influenced by season ($p < 0.01$), species ($p < 0.01$), and their interaction ($p < 0.05$), the K release rate was only affected by season ($p < 0.01$). Additionally, the decomposition rate k differed within species types, *P. lucens* had the highest decay constant in the dry season (0.25), while *F. albida* had the highest k in the rainy season (0.55). Average DM decomposition, and N, P and K release rates of trees/shrubs leaves in the rainy season were 205%, 217%, 194%, and 225%, respectively higher ($p < 0.01$) than those of the dry season (Table 5 and Supplementary Table S7). During dry season *P. lucens* had 0.5-6-fold higher decay constants for DM loss, and N and P release compared with the other tree/shrub species. *F. albida* decomposition rate in the rainy season was 358% higher ($p = 0.03$) than that in the dry season. Similarly, the average decay constant of other tree/shrub during the dry season was four-folds lower ($p < 0.01$) than that of *F. albida*. Nitrogen and P release by *P. lucens* in dry season were 69% and 58%, respectively lower ($p < 0.01$) than those in the rainy season. While N and P release rates of *P.*

lucens in the rainy season were 5.4 times and 5.8 times, respectively higher ($p < 0.05$) than the average of others trees/shrubs leaves, its K release was 1.2-folds lower than the average of other species in the dry season.

Table 5. Decomposition and nutrients mineralization rate constants k (% day⁻¹) of leguminous (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) trees/shrubs leaves after 52 weeks in litterbags placed across season in Katibougou in the Sudano-Sahelian zone of Koulikoro in Mali (rainy, n=5 and dry, n=4).

In Burkina Faso, season and species significantly affected decomposition, and nutrient (N, P and K) release rate constants (Table 6 and Supplementary Table S8; $p < 0.01$). Except for the K release rate, there was a season and species interaction effect on decay constants. Average decomposition rate and N, P, and K release rates in the rainy season were 373%, 166%, 209% and 174% respectively, higher ($p < 0.01$) than those in the dry season. *Faidherbia albida* and *P. lucens* decomposition rates in dry season were five-folds lower than in the rainy season. Nitrogen, P and K release rates of *P. lucens* in rainy season were 325%, 567%, and 284%, respectively, higher ($p < 0.01$) than its N, P and K release rates in the dry season. *K. senegalensis* exhibited the lowest decomposition and N, P, and K release rates in both seasons compared with the other species.

Table 6. Decomposition and nutrients mineralization rate constants k (% day⁻¹) of leguminous (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) trees/shrubs leaves after 52 weeks in litterbags placed across season in Saria in the Sudano-Sahelian zone of West Central in Burkina Faso (rainy, n=5 and dry, n=4)

Among the soil chemical properties (N, P, K, Mg, Ca, and pH), and initial leaf chemistry (N, P, K, Mg, Ca, TP, and CT) and climatic data (rainfall, relative humidity and temperature), it was only soil pH, plant leafy K, P, and CT and annual average rainfall which had a significant effect on decomposition rate (Table 7). Whist soil pH and plant leaves CT negatively ($p < 0.01$; $p = 0.09$, respectively) influenced dry weight decomposition rate, initial tree/shrub leaves K, Mg, and P and annual rainfall positively ($p = 0.03$; $p = 0.02$; $p = 0.06$; $p < 0.01$, respectively) influenced dry weight decomposition rate.

Table 7. The effect of initial soil pH, and K, P, Mg, P, and condensed tannin (CT) from initial plant material and annual average rainfall on dry weight decomposition rate using a general linear model analysis

In general, nutrient inputs by leafy biomass varied across species in all three countries, except for K in Senegal, and P during dry season in Burkina Faso. In both Mali and Burkina Faso leafy biomass completely decomposed within 52 weeks after soil application, leading to a complete release of the applied nutrients.

In Senegal, the amounts of N applied from *P. lucens* were 76%, 40%, and 53% higher ($p < 0.01$) than of *G. senegalensis*, *F. albida* and *P. reticulatum*, respectively (Table 8), while the amounts of N remaining at 52 weeks after placement for *P. lucens* were 78%, 14%, and 77% lower ($p < 0.01$) than those of *G. senegalensis*, *F. albida*, and *P. reticulatum*, respectively. The amounts of P applied from *F. albida* were 17%, 32%, and 33% lower ($p = 0.03$) than those of *G. senegalensis*, *P. lucens*, and *P. reticulatum*, respectively. Similarly, the amounts of P remaining 52 weeks after placement by *G. senegalensis* and *P. reticulatum* were 5-folds higher ($p < 0.01$) than in *F. albida* leaves. While applied K did not vary between species, the amounts of K remaining in leaves from *F. albida*, *G. senegalensis* and *P. lucens* were 403%, 69%, and 669%, respectively lower ($p < 0.01$) than that of *P. reticulatum*.

Table 8. Applied nutrients and nutrients remaining from leguminous (*F. albida*, *P. lucens* and *P. reticulatum*) and non-leguminous (*G. senegalensis*) trees/shrubs leaves after 52 weeks in litterbags placed during the rainy season in Dahra in the Sahelian zone of Louga in Senegal, (n=5)

In dry season Mali, the amount of N applied from *F. albida* was two-folds greater ($p < 0.01$) than the average of the other tree/shrub leaves (Table 9). In the rainy season, average amount of N applied from *F. albida* and *P. lucens* was 126% larger ($p < 0.01$) than the average of *K. senegalensis* and *V. paradoxa*. Average amount of P applied from the other tree/shrub leaves in dry season, was three-folds greater ($p = 0.03$) than that of *P. lucens*, whereas average amount of P applied from *K. senegalensis* and *V. paradoxa* in the rainy season was 48% lower ($p = 0.04$) than the average of *F. albida* and *P. lucens*. In both, the dry and rainy seasons, the amount of K applied with *K. senegalensis* was 67% and 79%, respectively, greater ($p < 0.01$) than the average amount applied for *F. albida*, *P. lucens*, and *V. paradoxa*.

Table 9. Applied nutrients and nutrients remaining from leguminous (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) trees/shrubs leaves after 52 weeks in litterbags placed during the dry and the rainy season in Katibougou in the Sudano-Sahelian zone of Koulikoro in Mali (rainy, n=5 and dry, n=4)

In Burkina Faso, *P. lucens* had the highest and *K. senegalensis* the lowest N application rate in both seasons ($p < 0.01$) (Table 10). While in the dry season P application rate was similar for all species, in the rainy season, the amount of P applied from *F. albida*, *K. senegalensis*, and *V. paradoxa* were 83%, 78% and 79%, respectively, lower ($p < 0.01$) than that of *P. lucens*. Whilst the average amounts of K applied in the dry season from *F. albida*, *P. lucens*, and *V. paradoxa* were 140% greater ($p < 0.01$) than that of *K. senegalensis*, in the rainy season, the average amounts of K applied of *K. senegalensis*, *P. lucens*, and *V. paradoxa* was two-folds higher ($p = 0.02$) than that of *F. albida*.

Table 10. Applied nutrients and nutrients remaining from leguminous (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) trees/shrubs leaves after 52 weeks in litterbags placed during the dry and the rainy season in Saria in the Sudano-Sahelian zone of West Central in Burkina Faso (rainy, n=5 and dry, n=4)

Discussion

The findings of our study confirm the hypothesis that nutrient concentrations in tree/ shrub leafy biomass undergo seasonal variation. Like other studies in Brazil ²⁰, China ²², Nigeria ³⁴, and India ³⁵ we observed higher N, P, and K concentrations in leaves from the rainy season than in those of the dry season. High leaf N, P, and K concentrations in the rainy season likely result from an improved uptake of these nutrients from the soil solution due to increased litter decomposition and mineralization ^{21,35}. In addition, upon the onset of the rainy season, trees and shrubs typically produce new leaves, which contain higher nutrient concentrations than older leaves. Contrary to our finding, ^{19,23,25} reported higher K concentration in tree leaves of the dry season than of the rainy season from Ethiopia, Nigeria, and Ghana, respectively. An important K source in Sub-Saharan Africa is dust carried from the Sahara desert with the Harmattan winds ^{8,26}. The fallout of these winds reach regions closer to the Sahara desert, such as the study locations, more than coastal ones and lead to a substantial input of K ³⁶. In addition, K is not bound to organic compounds thus highly mobile, making it prone to leaching ³⁷. The two-fold higher rainfall in the above-mentioned study regions compared with our study locations may have led to leaching of K during the rainy season.

Our observation of high total phenol and condensed tannin concentrations in the dry season confirms findings of other authors ³⁸⁻⁴⁰. As an adaptation response to moisture and nutrient availability, particularly nitrogen, trees tend to increase condensed tannin production to protect already acquired leaf resources from herbivory ³⁹ but also from fungal attack. Hence, trees' preferential allocation of C for leaf defence instead growth leads to higher tannin concentrations in the dry season. Additionally, trees exposed to high solar radiation and under nutrient stress, tend to increase phenolics production to prevent photodamage from excess light energy ⁴¹.

Irrespective of location and season average N, P, and Mg concentrations in leguminous trees/shrubs leaves of *F. albida*, *P. lucens*, and *P. reticulatum* were significantly higher than in non-leguminous trees/shrubs leaves (*G. senegalensis*, *K. senegalensis*, and *V. paradoxa*). Average N concentration in leguminous tree and shrub leaves (22 mg g⁻¹) is comparable with the reported concentration of 20 mg g⁻¹ in the Sudanian savanna of Ghana ⁴². Average P concentration of leguminous species (1.5 mg g⁻¹) fall within the range (1.4 to 1.6) reported by ²³ in Ethiopia. Similarly, our average Mg concentration recorded in leguminous leaves of 3.6 mg g⁻¹ is in the range of 3.4 mg g⁻¹ to 6.7 mg g⁻¹ reported by ²⁹ from Ghana. Leguminous trees/shrubs species accumulate higher N concentration by fixing atmospheric N₂ through their association with N₂-fixing bacteria ⁴³. Because legumes require high amounts of P for N₂ fixation ⁴⁴ and Mg to support host legume and rhizobia growth ⁴⁵, legumes associate with arbuscular mycorrhiza which are known to be more efficient at scavenging for these nutrients than those in non-legumes ⁴⁴. Our data show that non-legumes accumulated more total phenol and condensed tannin than legumes, which confirmed observations made by ⁴⁶ and ⁴⁷. Given their protein binding properties condensed tannins are a powerful plant defence against predators and herbivores ³⁹ by reducing leaf palatability and digestibility ⁴⁸. Under N limiting

conditions, as it was likely the case for non-leguminous tree/shrub species at the study locations, plants allocate more C to carbon-based secondary compounds such as condensed tannins, when C accumulates in excess of growth demands ⁴⁹.

Despite being legumes, in both Burkina Faso and Mali seasonality had no effect on N concentration of *F. albida*, however, for *P. lucens*, N concentration in the dry season was 35% lower than in the rainy season. Contrary to *P. lucens* which it sheds leaves in the dry season ⁵⁰, *F. albida* maintains leaves in the dry season ⁵¹. Consequently, reduced transfer of C from leaves of *P. lucens* to rhizobia in the dry season may have limited N₂ fixation and ultimately reduced N concentration in the leaves during dry season, whereas *F. albida* was able to maintain its N₂ fixing capacity during both seasons.

Across locations and seasons, results showed that average decomposition rate of 0.23 *k* week⁻¹ obtained fall within the range of 0.02 to 0.41 *k* week⁻¹ reported for tree/shrub leaves decomposition rates in Burkina Faso and Nigeria ^{11,52,53}. The initial rapid decomposition found in our study across countries and seasons, may be attributed to the break down and leaching of soluble components such as sugar, starch, and amino acids as earlier reported ^(25, 54) the rate of release of K was 55% faster than that of N and 18% faster than of P. It was also 42% faster than DM losses. These observations support the findings by ⁵⁵ and ⁴⁷ Palm and Sanchez (1990) and Bayala et al. (2005) and reflecting easy leaching of this highly soluble nutrient ^{55,56}. Seasonality affected decomposition and nutrient release rates from leaves, with the rainy season having 155%, 97%, 112%, and 115% higher decomposition rates and N, P, and K release rates, respectively, than in the dry season. Similar findings have been reported by ⁵⁷ from Ethiopia and Brazil ²⁰. The decomposition rate is influenced by the quality of the plant residues: high quality residues with low C:N ratios decompose faster in moist conditions ⁵⁸. The effects of rainfall on decomposition of plant residue is attributable to rainfall-enhanced moisture availability. Moisture availability is crucial for microbial activity and nutrient release, supporting its positive effect on decomposition rate in our study. Thus the fast decomposition and nutrient release during the rainy season was caused by higher soil moisture, which promotes soil fauna activity and enzymatic processes ^{18,20}. Rainfall promoting litter decomposition and nutrient release have been reported by earlier studies in Costa Rica ⁵⁶ and Eastern Africa ⁵⁹. Aside soil moisture, the combination between warm temperature and high humidity in the rainy season is well known to hasten microbial activity which increases decomposition and nutrient release in the rainy season ^{16,22}. While there was no significant differences average annual temperature between both dry and rainy season at any of our study locations, the average relative humidity in rainy season was 97% higher than in dry season. In contrast to our findings, ¹⁴ noted that *Albizia gummifera* G. F. Gmel. leaves decompose 3% faster in the dry season than in the rainy season of Ethiopia. The disparity between our finding and that of the above author is attributed to seasonal differences between study sites. Compared with our study sites which do not experience rains during the dry season, ¹⁴ stated that at their study location sporadic rainfalls occurred the dry season which increased decomposition under high temperature.

The average decomposition rate of leguminous trees/shrubs leafy biomass was 1.4-fold higher than of non-leguminous tree/shrub leaves confirming findings by ²⁷ and ¹¹. The compared with their non-leguminous counterparts higher initial leaf N, P, and Mg concentrations in leguminous tree/shrub leaves were found to be positively correlated with decomposition ^{60,61}. Contrarily, non-leguminous tree/shrub trees had higher C/N ratios and

larger concentrations of total phenols and condensed tannins, which have been reported to negatively affect decomposition^{62,63}. A low C/N ratio facilitates the breakdown of organic matter whereby C/N ratios optimal for decomposition processes range from 20 to 30⁶⁴. In our study non-leguminous leaves had a C/N ratio of 37 compared with 22 in legume species, resulting in their slower decomposition even though no statistically significant influence of the C/N ratio was found in our overall analysis of mineralization determinants. The positive effect of P on leaf decomposition in our study supports earlier work that acknowledged its pivotal role in litter decomposition within terrestrial ecosystems^{65–67}. Similar results on matter decomposition have been reported from northern Arizona⁶⁸ and China⁶⁵. Condensed tannins are essential determinants of decomposition³² because of their antimicrobial activity and high reactivity with N and related compounds. High condensed tannin levels in initial leaves have been reported to slower decomposition rates^{32,33}.

Materials and methods

Study area

The study was conducted at Dahra (15.2410° N, 15.2556° W) in the Sahelian ecological zone of Senegal and at Koulikoro (17.5707° N, 3.9962° W) and Saria (12.2383° N, 1.5616° W) in the Sudano-Sahelian ecological zones of Mali and Burkina Faso, respectively. In 2021 annual rainfall in Dahra was 420 mm with 74% (309 mm) of rainfall occurring in August. In Dahra, average annual temperature was 29 °C of which the highest temperature of 32°C was recorded in April and June, and the lowest temperature of 25°C in January. For Koulikoro, average annual rainfall was 705 mm in 2021 with July having the highest rainfall (233 mm corresponded to 33% of the total annual rainfall). The annual average temperature was 28°C with a maximum of 33°C occurring the April, and May a minimum of 24°C occurring in December and January. From 2021-2022 in Saria, the 2-year average rainfall was 980 mm with 230 mm occurring in August, and annual temperature averaging 28°C with a monthly high of 31°C occurring in March, April, and May and an average low of 25°C in December (Fané, unpublished data records). Soils at the study locations of Mali and Burkina Faso are classified as Ferrasols⁶⁹, and Arenosols for Senegal⁷⁰, with pH ranging from 4.93 to 6.15 and major elements ranging from 2.92 to 4.53 mg C g⁻¹ soil, 0.26 to 0.42 mg N g⁻¹ soil, 0.17-0.21 mg P g⁻¹ soil, 0.05-0.41 mg K g⁻¹, 0.16-0.24 mg Ca g⁻¹ soil, and 0.16-0.23 mg Mg g⁻¹ soil (Fané, unpublished data; Table 11). At all study locations, the vegetation consists of open parklands with continuous grasses and scattered trees^{71–73}.

Table 11. Top soil (0-20) chemical properties for Dahra in Senegal, Koulikoro in Mali, and Saria in Burkina Faso (n = 3).

Data collection

At each location the decomposition of leafy biomass of four different plant species were investigated: in Mali and Burkina Faso the non-legume species *V. paradoxa*, *K. senegalensis* with the legume species *F. albida*, *Pterocarpus lucens* Lepr., and in Senegal with legume species *F. albida*, *P. lucens*, *P. reticulatum* and non-legume species *G. senegalensis*. Senegal's species composition differed from that of Mali and Burkina Faso because of the absence of natural stands of *V. paradoxa* and *K. senegalensis* in Dahra (Senegal). The decomposition and nutrients release patterns of the plant leaves were studied using the litterbag technique using 20 cm × 20 cm nylon bags with a mesh size of 2 mm in the dry (from January 2022 to

February 2023) and rainy (from June 2021 to July 2022) seasons of Mali and Burkina Faso. For Senegal, the study was conducted only in the rainy season because of limited availability of plant material in the dry season. Each litterbag was filled with fresh leaves equivalent to 26 g DM for rainy season and 17 g DM for the dry season. In each country per season a total of 120 litterbags were buried at the depth of 15 cm (plough depth) with a 50 cm spacing between the litterbags and arranged in a complete randomized design in five for the rainy and four replications for the dry season. The litterbags were collected 2, 4, 8, 16, 32 and 52 weeks after placement in five and four respective replicates for the rainy and dry seasons. Leaves remaining in the litterbag at each sampling time were carefully separated from soil and organic debris using a brush, oven dried at 60°C for 72 hrs, weighed, and milled.

Chemical analysis

Carbon (C) and nitrogen (N) concentration in the milled samples were analysed by high-temperature combustion using a Vario Max CHN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). For the determination of phosphorus (P), potassium (K), and magnesium (Mg) concentrations milled samples were ashed at 550 °C for 24 hours and the remaining ash was digested with HCl (32% hydrochloric acid) to remove soil particles. The nutrients in the ashing solution were measured by inductively coupled plasma optical emission spectroscopy (Spectrogreen ICP-OES, SPECTRO Analytical Instruments GmbH, Kleve, Germany). Total phenol contents were determined using the Folin-Ciocalteu method^{74,75} in aqueous acetone (70% v/v) as extractant⁷⁶. Total tannins were analyzed by subtracting non-tannin phenols (NTP) after precipitating tannins with polyvinyl polypyrrolidone from total phenols (TP). Condensed tannins (CT) were assessed using the butanol-HCl method, with a 95:5 v/v ratio of butanol to HCl⁷⁶.

Data analysis

Mineral soil contamination of samples was corrected by using the ash content as an indicator as it performed statistically better than chromium (Cr), iron (Fe) and aluminium (Al) contents (Supplementary Tables S3, S4, S5). To this end the equation modified after Potthoff and Loftfield (1998) as described by²⁵ was used:

$$DM_{LB} (g) \times C_{LB} \left(\frac{mg}{g} \right) = DM_S (g) \times C_S \left(\frac{mg}{g} \right) + DM_L (g) \times C_L \left(\frac{mg}{g} \right) \quad (1)$$

$$DM_{LB} (g) = DM_S (g) + DM_L (g) \quad (2)$$

The two equations were combined, resulting in Eq. 3, which was used to estimate the contamination of litterbag content by soil particles.

$$DM_S (g) = \frac{DM_{LB} (g) \times [C_{LB} \left(\frac{mg}{g} \right) - C_L \left(\frac{mg}{g} \right)]}{C_S \left(\frac{mg}{g} \right) - C_L \left(\frac{mg}{g} \right)} \quad (3)$$

where DM_S (g) is the soil DM (actual contamination), DM_{LB} (g) is the litterbag DM, C_{LB} ($\frac{mg}{g}$) is the ash concentration in litterbags, C_S ($\frac{mg}{g}$) is the ash concentration in the soil, and C_L ($\frac{mg}{g}$) is the ash concentration in litter/leaves.

The percent dry weight or nutrient remaining in the litterbag at each sampling time was determined using the following equation:

$$DM_r (\%) = \left(\frac{DM_t}{DM_0} \right) \times 100 \quad (4)$$

where DM_r is the % dry matter or nutrient quantity of leaves remaining in the litterbag at each sampling time, DM_t is the dry matter or nutrient content of leaves remaining in the litterbag at each sampling time, and DM_0 is the initial dry weight or nutrient content of the leaves.

Rates of decomposition and nutrient release were estimated with Sigmaplot 15 (Systat Software Inc., San Jose, CA, USA) using the two-parameter exponential model proposed by Olson (1963): $Y = \beta_i e^{-kt}$, where Y is the remaining material at sampling time t in percent of the initial material, β_i is the recalcitrant pool fraction of species i and k is the decay or nutrient release rate.

T-tests were used to compare initial nutrient concentration, decomposition and nutrient release rates between species types (legumes and non-legumes). One-way analysis of variance (ANOVA) was employed to compare plant leaves' initial nutrient concentration, and their decomposition and nutrient release rates in Senegal. In Mali and Burkina Faso, two-way ANOVA was used to test the interaction between different plant leaves and seasonality on leaves' initial nutrient concentration, and their decomposition and nutrient release rates. Data violating the assumptions of ANOVA were transformed using the Tukey ladder of powers. The generalised linear model assuming a Gaussian error distribution was used to determine the soil (N, P, K, Mg, Ca and pH), and initial leaves chemical (N, P, K, Mg, Ca, TP and CT) properties and climate data (rainfall, relative humidity and temperature) affecting the decomposition rate of tree/shrub leaves at the study locations. To this end, non-significant variables were sequentially removed from the model by eliminating the one with the highest p value until all remaining variables were significant. Prior to fitting the model, rates of leaf decomposition were log transformed to satisfy the linearity assumption of the model. All statistics were performed using the R statistical software version 4.3.3⁷⁹.

Conclusions

The results of this study showed that season significantly influenced chemical properties of the evaluated leguminous tree/shrub species. The decomposition rates and nutrient release patterns across locations were higher during the rainy season especially for leaves of species with higher concentrations of N, P, and K compared with observations for the dry season. In contrast, C/N ratio, total phenol and condensed tannin concentrations of leaves were higher in the dry than in the rainy season. Results also showed that the leaves of tree/shrub species differed in chemical properties, whereby leguminous tree/shrub leaves recorded higher N, P and Mg concentrations than their non-leguminous species. The leaves of non-leguminous trees/shrubs on the other hand, recorded higher concentrations of total phenols, K, and condensed tannins. Decomposition rates of leguminous tree/shrub leafy biomass were higher

than of non-leguminous tree/shrub leaves which is attributable to the higher nutrient concentrations and lower total phenol concentrations in legumes.

To improve their application efficiency at the farm level, leaf mulching should be tailored according to the species type and rate of biomass application for a particular environment. This will help to optimize synchronization of nutrient release with crop nutrient demands. Overall, the leaves of leguminous tree/shrub seem better suited for use as organic fertilizers for crops to meet earlier nutrient demands by crops, whereas non-leguminous tree/shrub leaves appear more suitable for use as long-term soil conditioners and slow-release organic fertilizers.

Data Availability

Data is provided within the manuscript and original data can be obtained from the corresponding author upon reasonable request.

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Statements & Declarations

Author contribution

S.F. and D.K.A. did the field work and wrote the main manuscript text, M.I provided methodological support and contributed in the first draft writing, C.N. contributed in the field work and with data, S.S. contributed with data and advise, and A.B. conceptualised the study and secured funding. All authors reviewed the manuscript.

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this manuscript.

Plant material identification

The species studied were identified and authenticated by Dr Sidi Sanogo, researcher, and curator of the herbarium (<http://sciweb.nybg.org/science2/indexherbariorum.asp>) at the Institut d'Economie Rurale (IER) du Mali and a co-author of the manuscript. Samples of seeds and/or herbariums observed: *Faidherbia albida* (129-UPP000), *Piliostigma reticulatum* (227-UPP-068), *Pterocarpus lucens* (237-UPP-072), *Khaya senegalensis* (169-UPP-029-1) and *Guiera senegalensis* (ML-USFH-79).

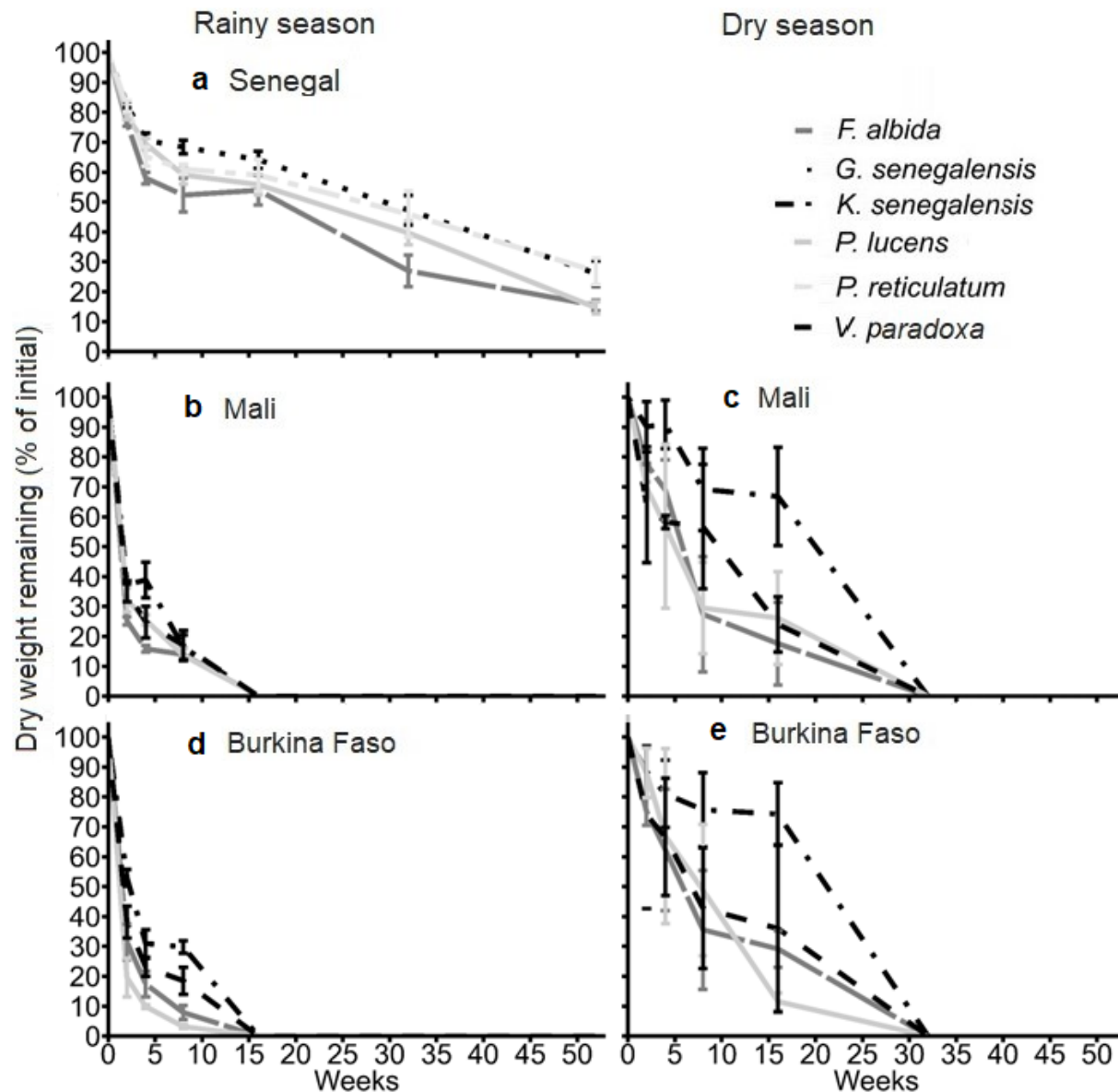


Fig. 1. Decay patterns of different tree/shrub leaves after 52 weeks in litterbags placed in soil across season in Dahra in the Sahelian zone of Louga in Senegal, Katibougou and Saria in the Sudano-Sahelian zone of Koulikoro and West Central in Mali and Burkina Faso respectively. Error bars indicate $\pm$ one standard error of mean (n=5)

828 **Table 1.** Initial chemical properties of trees/shrubs leaves subjected decomposition study in Dahra, Sahelian zone of Senegal (n = 3)

Species	N	P	K	Mg	C:N	Total Phenols	Condensed-Tannin
	mg g ⁻¹						
<i>F. albida</i>	19.35 (1.05) b	0.97 (0.01) b	6.74 (0.70)	3.13 (0.22) b	24.13 (1.86) b	38.70 (0.66) b	19.74 (1.31) b
<i>G. senegalensis</i>	15.46 (0.08) c	1.17 (0.05) ab	7.41 (0.07)	2.80 (0.05) b	31.31 (0.12) a	42.41 (0.08) a	18.51 (1.36) b
<i>P. lucens</i>	27.16 (0.42) a	1.43 (0.14) a	10.20 (4.10)	5.84 (1.46) a	17.95 (0.24) c	32.81 (0.64) c	55.53 (2.34) a
<i>P. reticulatum</i>	17.72 (0.68) b	1.44 (0.14) a	8.06 (0.32)	2.57 (0.09) b	26.02 (0.41) b	24.96 (0.36) d	1.55 (0.83) c
F value	58.98	4.91	0.52	4.22	32.94	108.20	145.59
p-value	< 0.01	0.03	0.68	0.04	< 0.01	< 0.01	0.01

829 Means along the same columns with different lower-case letters show significant differences trees/shrubs leaves ($p < 0.05$). Numbers in bracket
 830 after trees/shrubs leaves means show $\pm$ one standard error of the mean.

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841 **Table 2.** Initial chemical properties of trees/shrubs leaves subjected to decomposition study in Koulikoro, Sudano-Sahelian zone of Mali (n = 3)

Season	Species	N	P	K	Mg	C:N	Total Phenols	Condensed-Tannin
mg g ⁻¹								
Dry		16.58 (1.57) A	1.32 (0.15) A	9.51 (0.78) A	3.68 (0.27) A	30.41 (1.94) A	72.18 (6.67) A	42.62 (5.09) A
	<i>F. albida</i>	25.07 (3.50) b	1.64 (0.00) ab	7.91 (0.02) ab	3.52 (0.01) abc	19.81 (101) a	59.82 (0.20) c	23.80 (0.17) a
	<i>K. senegalensis</i>	12.30 (0.25) a	1.51 (0.39) ab	12.22 (2.71) abc	3.44 (0.54) abc	36.37 (0.61) cd	80.42 (0.99) d	69.86 (0.14) f
	<i>P. lucens</i>	15.12 (0.33) a	0.59 (0.01) a	9.16 (0.14) ab	2.80 (0.05) ab	31.24 (0.50) b	44.82 (0.52) b	40.12 (0.12) e
	<i>V. paradoxa</i>	13.84 (0.08) a	1.56 (0.02) ab	8.73 (0.10) ab	4.97 (0.06) c	34.23 (0.10) bc	103.66 (1.41) e	36.69 (0.29) d
Rainy		20.80 (2.57) B	1.39 (0.17) A	11.51 (1.24) B	4.02 (0.33) A	27.10 (3.22) B	47.69 (10.06) B	30.23 (0.03) B
	<i>F. albida</i>	26.99 (5.60) b	1.87 (0.45) b	6.90 (1.74) a	4.25 (0.67) bc	17.31 (1.84) a	27.60 (0.48) a	15.04 (0.75) b
	<i>K. senegalensis</i>	12.85 (0.23) a	1.03 (0.09) ab	17.20 (0.27) c	2.28 (0.03) a	36.56 (0.42) cd	30.13 (0.24) a	34.86 (0.35) d
	<i>P. lucens</i>	30.72 (2.28) b	1.78 (0.16) b	12.81 (0.55) bc	4.77 (0.08) c	15.81 (0.71) a	27.57 (0.84) a	42.32 (0.87) e
	<i>V. paradoxa</i>	12.66 (0.11) a	0.87 (0.08) ab	9.12 (0.33) ab	4.77 (0.08) c	38.70 (0.27) d	105.44 (1.09) e	28.70 (0.85) c
Two-way ANOVA								
Season		F = 17.46 P < 0.01	F = 0.17 P = 0.68	F = 5.92 P = 0.03	F = 1.20 P = 0.29	F = 30.30 P < 0.01	F = 1761.58 P < 0.01	F = 682.86 P < 0.01
Species		F = 45.30 P < 0.01	F = 2.89 P = 0.07	F = 14.79 P < 0.01	F = 11.26 P < 0.01	F = 229.90 P < 0.01	F = 2778.29 P < 0.01	F = 860.67 P < 0.01
Season × Species		F = 14.48 P < 0.01	F = 7.22 P < 0.01	F = 2.87 P = 0.07	F = 9.76 P = 0.07	F = 50.62 P < 0.01	F = 359.14 P < 0.01	F = 280.74 P < 0.01

842 Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves and upper-case letters
 843 show significant differences between seasons (p < 0.05). Numbers in bracket after trees/shrubs leaves means show ± one standard error of the
 844 mean.

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848 **Table 3.** Initial chemical properties of different trees/shrubs leaves subjected to decomposition study in Saria, Sudano-Sahelian zone of Burkina
849 Faso (n = 3)

Season	Species	N	P	K	Mg	C:N	Total Phenols	Condensed-Tannin
mg g ⁻¹								
Dry		15.45 (1.42) A	0.71 (0.07) A	6.41 (0.69) A	2.76 (0.26) A	33.45 (2.86) A	88.19 (6.13) A	44.73 (4.26) A
	<i>F. albida</i>	17.54 (0.21) bc	0.72 (0.03) a	8.02 (0.35) bcd	2.36 (0.04) a	26.16 (0.12) b	97.12 (1.13) f	30.76 (0.52) c
	<i>K. senegalensis</i>	11.12 (0.11) a	0.57 (0.08) a	3.26 (0.30) a	2.33 (0.21) a	41.46 (0.38) cd	75.28 (0.93) e	48.67 (0.23) e
	<i>P. lucens</i>	21.94 (1.67) cd	0.96 (0.16) a	8.40 (0.01) bcd	2.50 (0.27) ab	22.23 (1.66) ab	63.80 (0.63) d	66.07 (1.08) g
	<i>V. paradoxa</i>	11.19 (0.02) a	0.59 (0.13) a	6.89 (1.45) abc	0.84 (0.27) bc	43.96 (0.01) d	116.56 (0.65) g	33.43 (0.05) c
Rainy		17.37 (1.64) B	1.67 (0.50) B	9.27 (0.89) B	3.42 (0.24) B	29.70 (2.38) B	52.60 (12.13) B	32.29 (5.59) B
	<i>F. albida</i>	17.18 (2.14) bc	0.72 (0.06) a	5.14 (0.50) ab	4.72 (0.03) c	26.81 (3.25) b	17.24 (0.12) a	10.52 (0.01) a
	<i>K. senegalensis</i>	12.36 (0.18) a	0.91 (0.08) a	10.13 (0.31) cd	2.52 (0.08) ab	37.86 (0.52) cd	40.42 (0.81) c	38.29 (1.34) d
	<i>P. lucens</i>	25.89 (0.32) d	4.18 (1.10) b	10.04 (2.16) cd	3.30 (0.05) abc	18.77 (0.23) a	31.99 (0.44) b	59.34 (1.34) f
	<i>V. paradoxa</i>	14.05 (0.18) ab	0.87 (0.05) a	11.76 (0.33) d	3.30 (0.05) ab	35.36 (0.36) c	120.75 (1.33) h	21.02 (0.62) b
Two-way ANOVA								
Season		F = 7.78 P = 0.01	F = 11.54 P = 0.04	F = 14.78 P = 0.01	F = 10.28 P = 0.01	F = 16.15 P < 0.01	F = 3630.69 P < 0.01	F = 451.78 P < 0.01
Species		F = 65.46 P < 0.01	F = 10.63 P < 0.01	F = 4.98 P = 0.01	F = 6.59 P = 0.01	F = 107.07 P < 0.01	F = 3026.78 P < 0.01	F = 1028.83 P < 0.01
Season × Species		F = 1.87 P = 0.18	F = 7.13 P < 0.01	F = 9.73 P < 0.01	F = 9.91 P < 0.01	F = 4.12 P = 0.02	F = 850.26 P < 0.01	F = 23.78 P < 0.01

850 Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves and upper-case letters
851 show significant differences between seasons.

Table 4. The mineralization rate constants (k : % day⁻¹) following the decomposition of leaves of leguminous trees/shrubs (*F. albida*, *P. lucens* and *P. reticulatum*) and non-leguminous (*G. senegalensis*) after 52 weeks in litterbags placed in soil during rainy season in Dahra in the Sahelian zone of Louga in Senegal (n=5).

Species	Mass loss	N	P	K
<i>F. albida</i>	0.14 (0.04) a	0.21 (0.04) a	0.63 (0.22) a	0.91 (0.17) a
<i>G. senegalensis</i>	0.07 (0.01) b	0.07 (0.02) b	0.21 (0.01) b	0.77 (0.08) a
<i>P. lucens</i>	0.14 (0.01) a	0.14 (0.02) a	0.42 (0.09) ab	0.84 (0.15) a
<i>P. reticulatum</i>	0.07 (0.01) b	0.07 (0.01) b	0.21 (0.04) b	0.35 (0.07) b
F value	4.99	5.86	3.37	3.92
p-value	0.02	<0.01	0.04	0.03

Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves ($p < 0.05$). Numbers in bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

Table 5. The mineralization rate constants (k : % day⁻¹) following the decomposition of leaves of leguminous trees/shrubs (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) after 52 weeks in litterbags placed across season in Katibougou in the Sudano-Sahelian zone of Koulikoro in Mali (rainy, n=5 and dry, n=4).

Season	Species	Mass loss	N	P	K
Dry		0.96 (0.09) A	0.84 (0.32) A	1.17 (0.39) A	1.12 (0.32) A
	<i>F. albida</i>	0.84 (0.14) ab	0.84 (0.14) ab	0.91 (0.07) ab	0.98 (0.14) ab
	<i>K. senegalensis</i>	0.42 (0.07) a	0.42 (0.07) a	0.35 (0.00) a	0.84 (0.21) a
	<i>P. lucens</i>	1.75 (0.07) abc	1.19 (0.42) ab	2.10 (0.63) ab	1.75 (0.35) abc
	<i>V. paradoxa</i>	0.84 (0.07) ab	0.91 (0.63) ab	1.33 (0.84) ab	0.91 (0.56) a
Rainy		2.94 (0.40) B	0.40 (0.33) B	2.66 (0.40) B	0.33 (0.47) B
	<i>F. albida</i>	3.85 (0.35) d	3.36 (0.28) cd	4.62 (0.42) c	3.43 (0.42) cd
	<i>K. senegalensis</i>	2.10 (0.28) abc	1.33 (0.21) ab	1.61 (0.21) ab	3.85 (0.63) d
	<i>P. lucens</i>	2.80 (0.49) bcd	3.85 (0.42) d	4.97 (0.49) c	3.15 (0.35) bcd
	<i>V. paradoxa</i>	3.01 (0.49) cd	2.10 (0.42) bc	2.59 (0.49) b	4.13 (0.49) d
Two-way ANOVA					
	Season	F = 45.89 P < 0.01	F = 51.04 P < 0.01	F = 9.66 P < 0.01	F = 58.67 P < 0.01
	Species	F = 3.61 P = 0.03	F = 9.86 P < 0.01	F = 13.55 P < 0.01	F = 0.26 P = 0.85
	Season × Species	F = 2.05 P = 0.13	F = 3.25 P = 0.04	F = 3.39 P = 0.03	F = 1.66 P = 0.20

Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves ($p < 0.05$). Numbers in bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

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889 **Table 6.** The mineralization rate constants (k : % day⁻¹) following the decomposition of leaves of leguminous trees/shrubs (*F. albida* and *P. lucens*) and non-
890 leguminous (*K. senegalensis* and *V. paradoxa*) after 52 weeks in litterbags placed across season in Saria in the Sudano-Sahelian zone of West
891 Central in Burkina Faso (rainy, n=5 and dry, n=4)

Season	Species	Mass loss	N	P	K
Dry		0.70 (0.26) A	1.02 (0.53) A	1.14 (0.27) A	1.58 (0.84) A
	<i>F. albida</i>	0.77 (0.21) a	0.70 (0.21) a	0.77 (0.28) ab	1.05 (0.35) ab
	<i>K. senegalensis</i>	0.28 (0.07) a	0.28 (0.07) a	0.35 (0.07) a	0.77 (0.28) a
	<i>P. lucens</i>	1.05 (0.56) a	1.12 (0.56) a	1.05 (0.49) ab	1.33 (0.56) ab
	<i>V. paradoxa</i>	0.70 (0.21) a	1.96 (1.26) ab	2.38 (0.24) ab	3.15 (2.17) ab
Rainy		3.31 (0.39) B	1.82 (0.37) B	3.50 (0.39) B	4.32 (0.51) B
	<i>F. albida</i>	3.71 (0.35) ab	2.80 (0.35) ab	3.71 (0.35) b	4.97 (0.42) b
	<i>K. senegalensis</i>	1.75 (0.21) a	0.91 (0.07) a	1.05 (0.07) ab	2.10 (0.28) ab
	<i>P. lucens</i>	5.04 (0.84) b	1.26 (0.84) b	7.00 (0.91) c	5.11 (0.77) b
	<i>V. paradoxa</i>	2.73 (0.14) ab	2.31 (0.21) ab	2.23 (0.21) ab	5.11 (0.56) b
Two-way ANOVA					
	Season	F = 90.06	F = 15.40	F = 19.98	F = 18.44
		P < 0.01	P < 0.01	P < 0.01	P < 0.01
	Species	F = 11.68	F = 6.77	F = 9.25	F = 3.80
		P < 0.01	P < 0.01	P < 0.01	P = 0.02
	Season × Species	F = 4.05	F = 3.44	F = 7.16	F = 1.11
		P = 0.02	P = 0.03	P = 0.01	P = 0.36

892 Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves ($p < 0.05$). Numbers in
893 bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

Table 7. The effect of initial soil pH, and K, P, Mg, P, and condensed tannin (CT) from initial plant material and annual average rainfall on dry weight decomposition rate using a general linear model analysis

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	8.184***	1.190	6.878	< 0.01
CT	-0.010.	0.006	-1.696	0.096
K	0.061*	0.027	2.232	0.030
Mg	0.177*	0.076	2.330	0.024
P	0.212.	0.109	1.949	0.057
pH	-2.230***	0.211	-10.558	< 0.01
Rainfall	0.001***	0.000	4.009	< 0.01

*Significant at $p < 0.05$, **Significant at $p < 0.01$, ***Significant at $p < 0.001$

919 **Table 8.** Applied nutrients and nutrients remaining from leaves of leguminous trees/shrubs (*F. albida*, *P. lucens* and *P. reticulatum*) and non-
 920 leguminous (*G. senegalensis*) after 52 weeks in litterbags placed during the rainy season in Dahra in the Sahelian zone of Louga in Senegal,
 921 (n=5)

Season	Species	Applied nutrients			Nutrient remaining after 52 weeks		
		N	P	K	N	P	K
		kg ha ⁻¹					
Rainy	<i>F. albida</i>	125.8 (6.8) b	6.3 (0.1) b	43.8 (4. 6)	22.5 (1.2) c	0.7 (0.0) b	1.6 (0.2) c
	<i>G. senegalensis</i>	100.5 (0.5) c	7.6 (0.3) ab	48.2 (0.5)	89.5 (0.4) a	3.6 (0.2) a	4.9 (0.1) b
	<i>P. lucens</i>	176.5 (2.7) a	9.3 (0.9) a	66.3 (26.7)	19.3 (0.3) c	0.5 (0.1) b	1.1 (0.4) c
	<i>P. reticulatum</i>	115.2 (4.4) b	9.4 (0.9) a	52.4 (2.1)	82.7 (3.2) b	3.3 (0.3) a	8.3 (0.3) a
	F	58.97	4.89	0.13	482.00	78.00	134.50
	P	<0.01	0.03	0.94	<0.01	<0.01	<0.01

922 Means along the same columns with different lower-case letters show significant differences between trees/shrubs leaves ($p < 0.05$). Numbers in
 923 bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

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Table 9. Applied nutrients and nutrients remaining from leaves of leguminous trees/shrubs (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) after 52 weeks in litterbags placed during the dry and the rainy season in Katibougou in the Sudano-Sahelian zone of Koulikoro in Mali (rainy, n=5 and dry, n=4)

Season	Species	Applied nutrients			Nutrient remaining after 52 weeks		
		N	P	K	N	P	K
		kg ha ⁻¹					
Dry		72.8 (4.7) A	5.9 (0.5) A	42.7 (4.0) A			
	<i>F. albida</i>	106.5 (8.6) b	7.1 (0.0) ab	33.6 (0.1) a	0	0	0
	<i>K. senegalensis</i>	61.5 (9.3) a	7.5 (2.0) ab	61.1 (14.7) ab	0	0	0
	<i>P. lucens</i>	64.3 (0.8) ab	2.5 (0.0) a	38.9 (0.6) a	0	0	0
	<i>V. paradoxa</i>	58.8 (0.2) a	6.6 (0.1) ab	37.1 (0.4) a	0	0	0
Rainy		135.2 (7.7) B	9.1 (1.3) B	74.8 (4.7) B			
	<i>F. albida</i>	175.4 (21.0) c	12.2 (3.1) b	44.9 (11.2) a	0	0	0
	<i>K. senegalensis</i>	83.5 (0.9) ab	6.7 (0.6) ab	111.8 (1.7) c	0	0	0
	<i>P. lucens</i>	199.7 (8.5) c	11.6 (1.0) b	83.3 (3.5) ab	0	0	0
	<i>V. paradoxa</i>	82.3 (0.4) ab	5.7 (0.5) ab	59.3 (2.2) ab	0	0	0
Two-way ANOVA							
	Season	F = 92.41 P < 0.01	F = 10.83 P < 0.01	F = 45.55 P < 0.01			
	Species	F = 33.64 P < 0.01	F = 2.39 P = 0.11	F = 18.62 P < 0.01			
	Season × Species	F = 16.82 P < 0.01	F = 6.66 P < 0.01	F = 03.79 P = 0.03			

Means along the same columns with different lower-case letters show significant differences between trees/shrubs ($p < 0.05$). Numbers in bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

Table 10. Applied nutrients and nutrients remaining from leaves of leguminous trees/shrubs (*F. albida* and *P. lucens*) and non-leguminous (*K. senegalensis* and *V. paradoxa*) after 52 weeks in litterbags placed during the dry and the rainy season in Saria in the Sudano-Sahelian zone of West Central in Burkina Faso (rainy, n=5 and dry, n=4)

Season	Species	Applied nutrients			Nutrient remaining after 52 weeks		
		N	P	K	N	P	K
		kg ha ⁻¹					
Dry		65.7 (2.2) A	3.0 (0.4) A	28.3 (2.3) A			
	<i>F. albida</i>	74.6 (0.9) ab	3.1 (0.1) a	34.1 (1.5) a	0	0	0
	<i>K. senegalensis</i>	47.3 (0.5) a	2.4 (0.3) a	13.8 (1.3) a	0	0	0
	<i>P. lucens</i>	93.3 (7.1) bc	4.1 (0.7) a	35.7 (0.0) a	0	0	0
	<i>V. paradoxa</i>	47.6 (0.1) a	2.5 (0.6) a	29.7 (6.2) a	0	0	0
Rainy		112.9 (4.6) B	10.9 (2.1) B	60.25 (5.4) B			
	<i>F. albida</i>	111.7 (13.9) c	4.7 (0.4) a	33.4 (3.2) a	0	0	0
	<i>K. senegalensis</i>	80.3 (1.2) b	5.9 (0.6) a	65.9 (2.0) b	0	0	0
	<i>P. lucens</i>	168.3 (2.1) d	27.2 (7.2) b	65.3 (14.1) b	0	0	0
	<i>V. paradoxa</i>	91.3 (1.2) bc	5.7 (0.3) a	76.4 (2.2) b	0	0	0
Two-way ANOVA							
	Season	F = 141.63	F = 18.62	F = 63.37			
		P < 0.01	P < 0.01	P < 0.01			
	Species	F = 58.74	F = 10.19	F = 5.01			
		P < 0.01	P < 0.01	P = 0.01			
	Season × Species	F = 5.75	F = 7.86	F = 8.79			
		P < 0.01	P < 0.01	P < 0.01			

Means along the same columns with different lower-case letters show significant differences trees/shrubs ($p < 0.05$). Numbers in bracket after trees/shrubs leaves means show $\pm$ one standard error of the mean.

945 **Table 11.** Top soil (0-20) chemical properties for Dahra in Senegal, Koulikoro in Mali, and Saria in Burkina Faso (n = 3).

Study sites	C	N	P	K	Ca	Mg	Al	Fe	Cr	pH
	mg g ⁻¹									
Senegal	2.92 (0.02)	0.26 (0.03)	0.16 (0.00)	0.05 (0.01)	0.16 (0.00)	0.16 (0.00)	3.13 (0.00)	2.60 (0.00)	0.01 (0.00)	6.15 (0.01)
Mali	3.46 (0.01)	0.28 (0.01)	0.17 (0.00)	0.33 (0.01)	0.24 (0.00)	0.21 (0.00)	3.41 (0.00)	2.60 (0.00)	0.04 (0.00)	5.28 (0.05)
Burkina Faso	4.53 (0.03)	0.42 (0.01)	0.21 (0.00)	0.41 (0.01)	0.23 (0.00)	0.23 (0.00)	3.41 (0.00)	2.61 (0.00)	0.04 (0.01)	4.93 (0.02)

946 Numbers in bracket below means show $\pm$ one standard error of the mean.

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